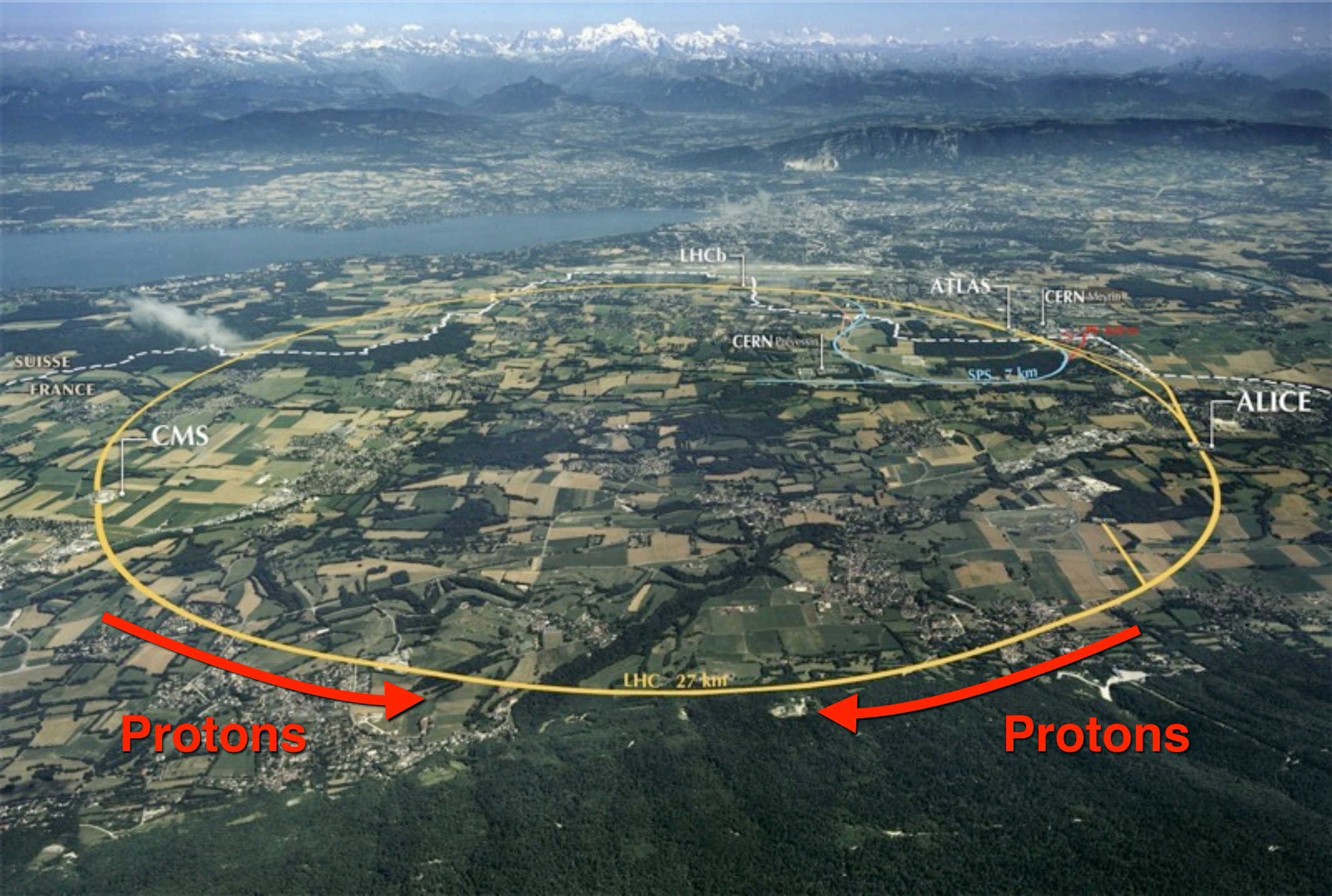


The Higgs Discovery

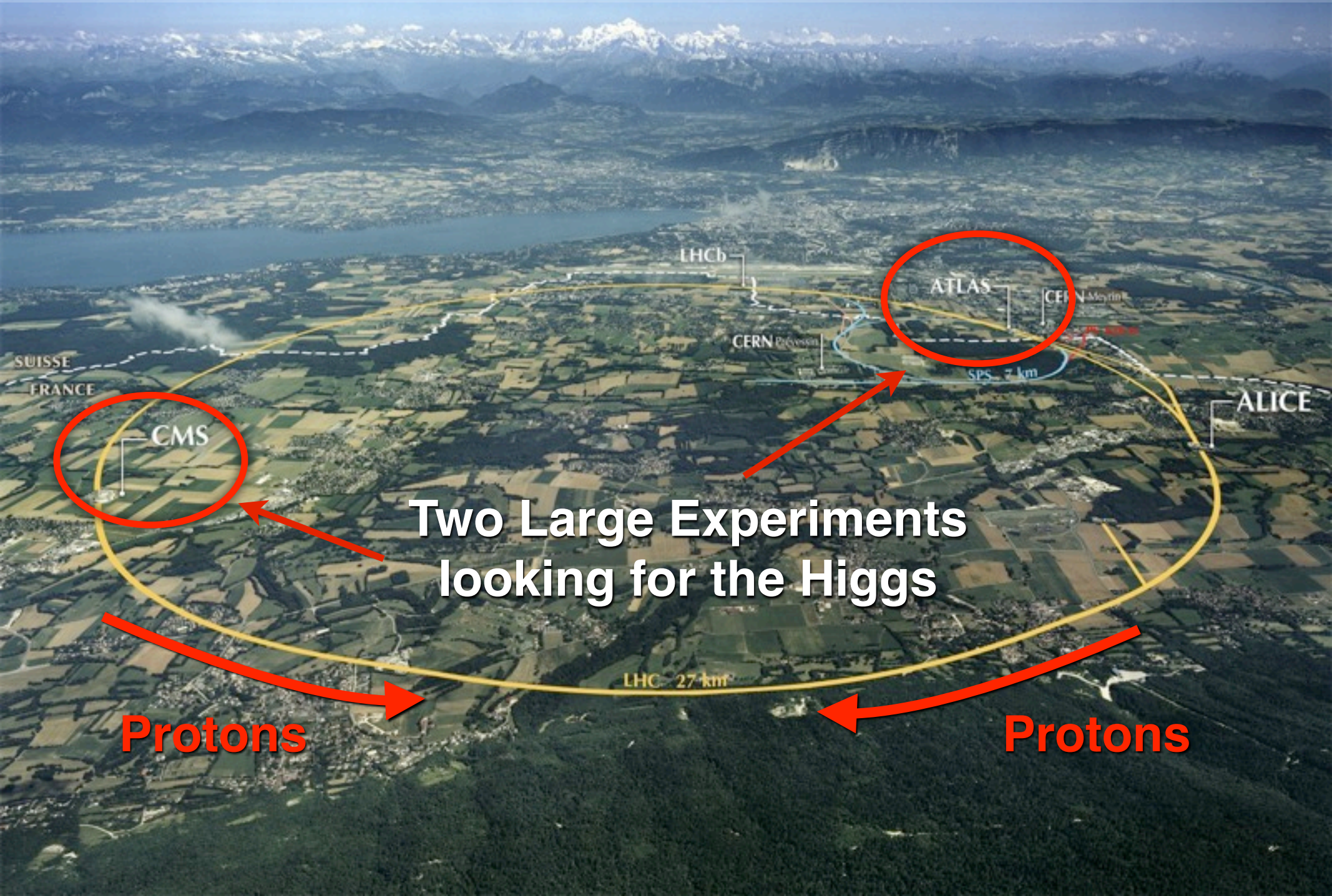
Elliot Lipeles

- What is the LHC?
- General Idea of why we build colliders
- Some sense of scale
- What we were looking for
- What we found
- What is left to find

The LHC: A Really Big Experiment



The LHC: A Really Big Experiment



LHCb

ATLAS

CERN Meyrin

CERN Prévessin

SPS 7 km

ALICE

CMS

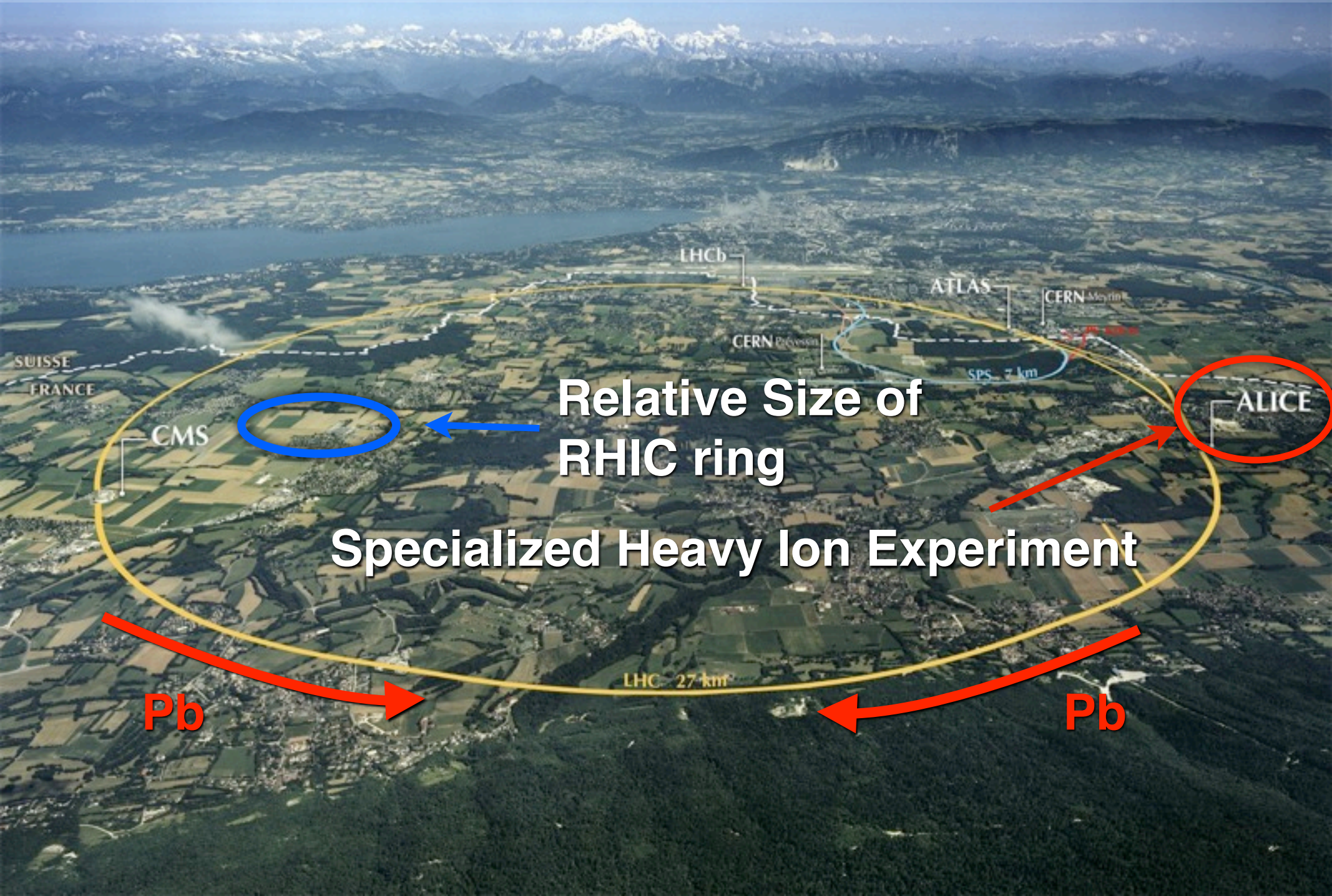
Two Large Experiments
looking for the Higgs

LHC 27 km

Protons

Protons

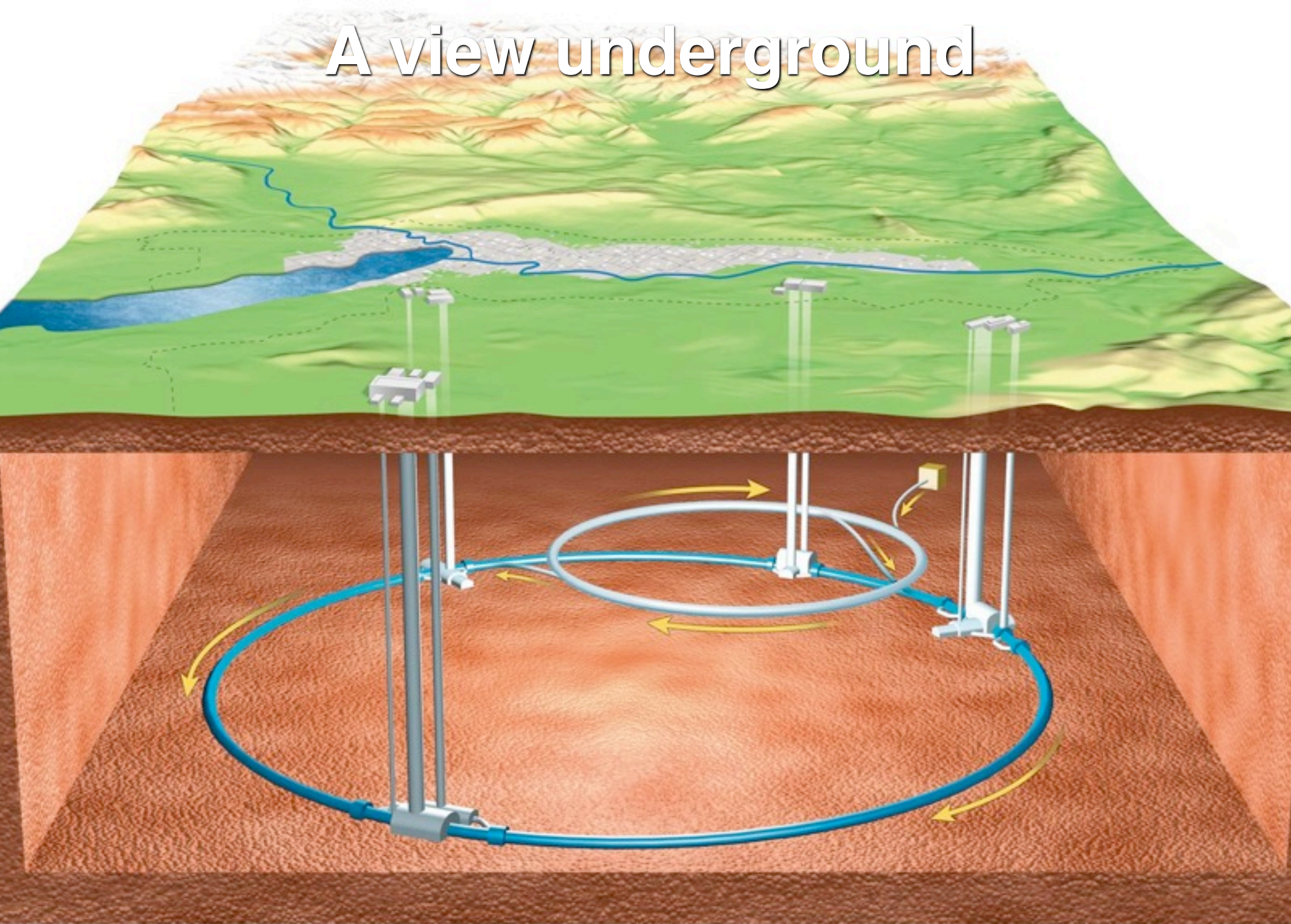
The LHC: A Really Big Experiment



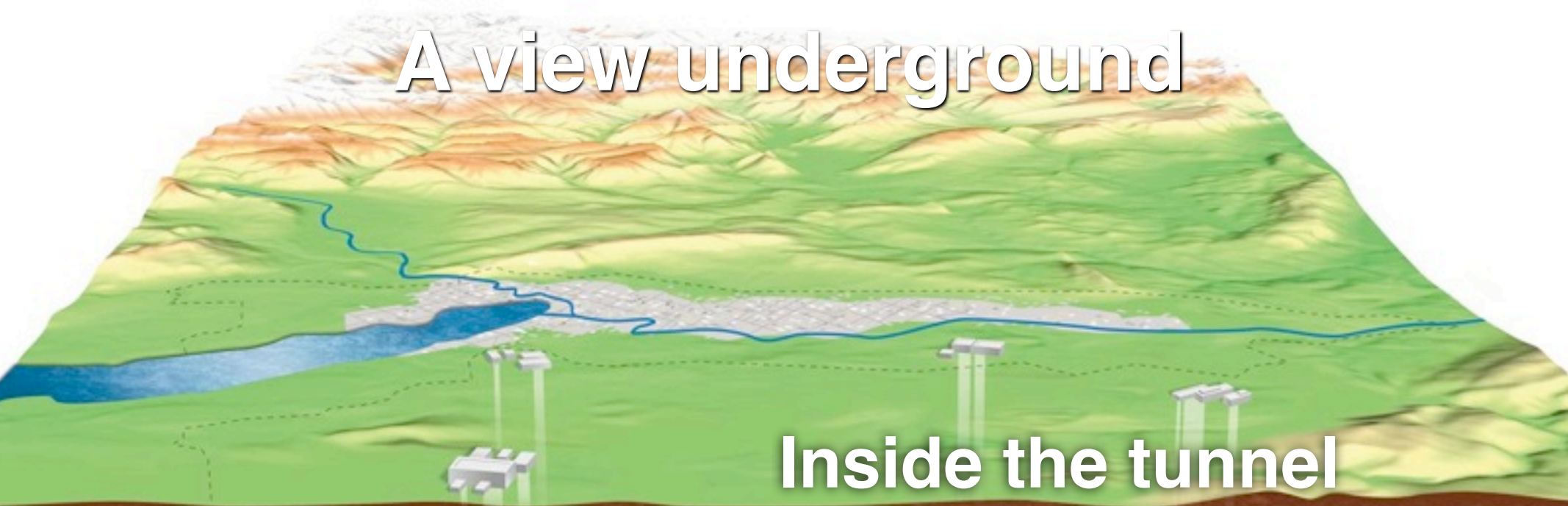
Relative Size of
RHIC ring

Specialized Heavy Ion Experiment

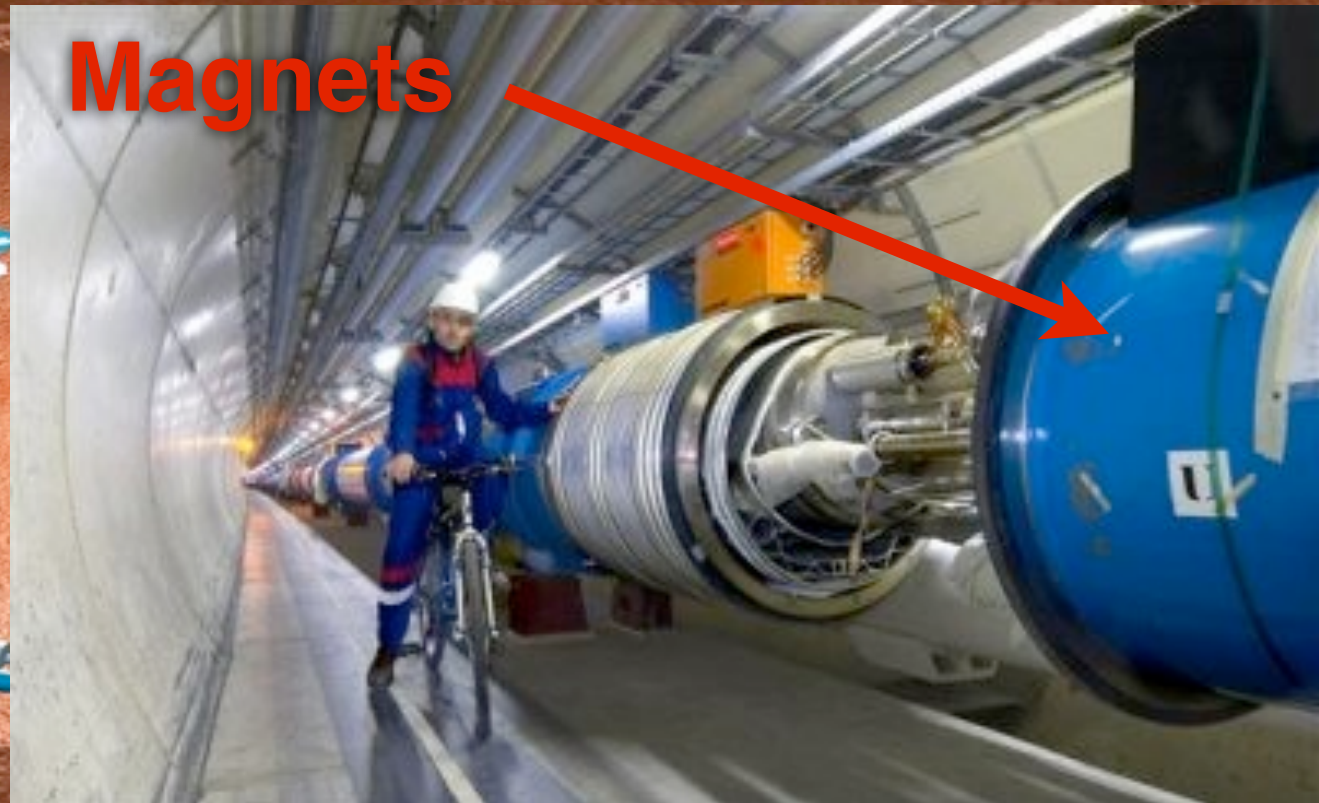
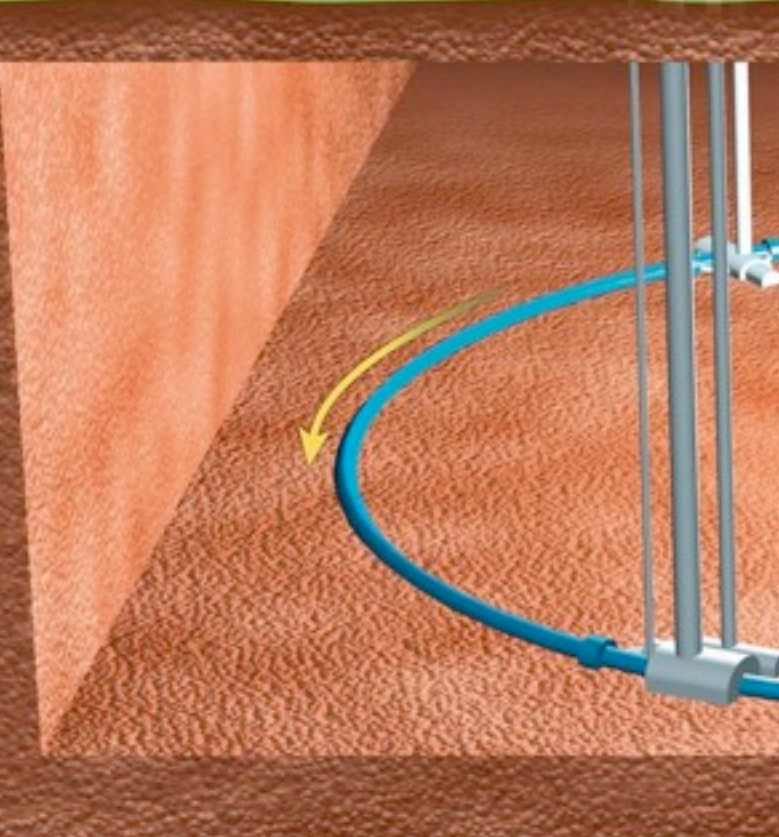
A view underground



A view underground

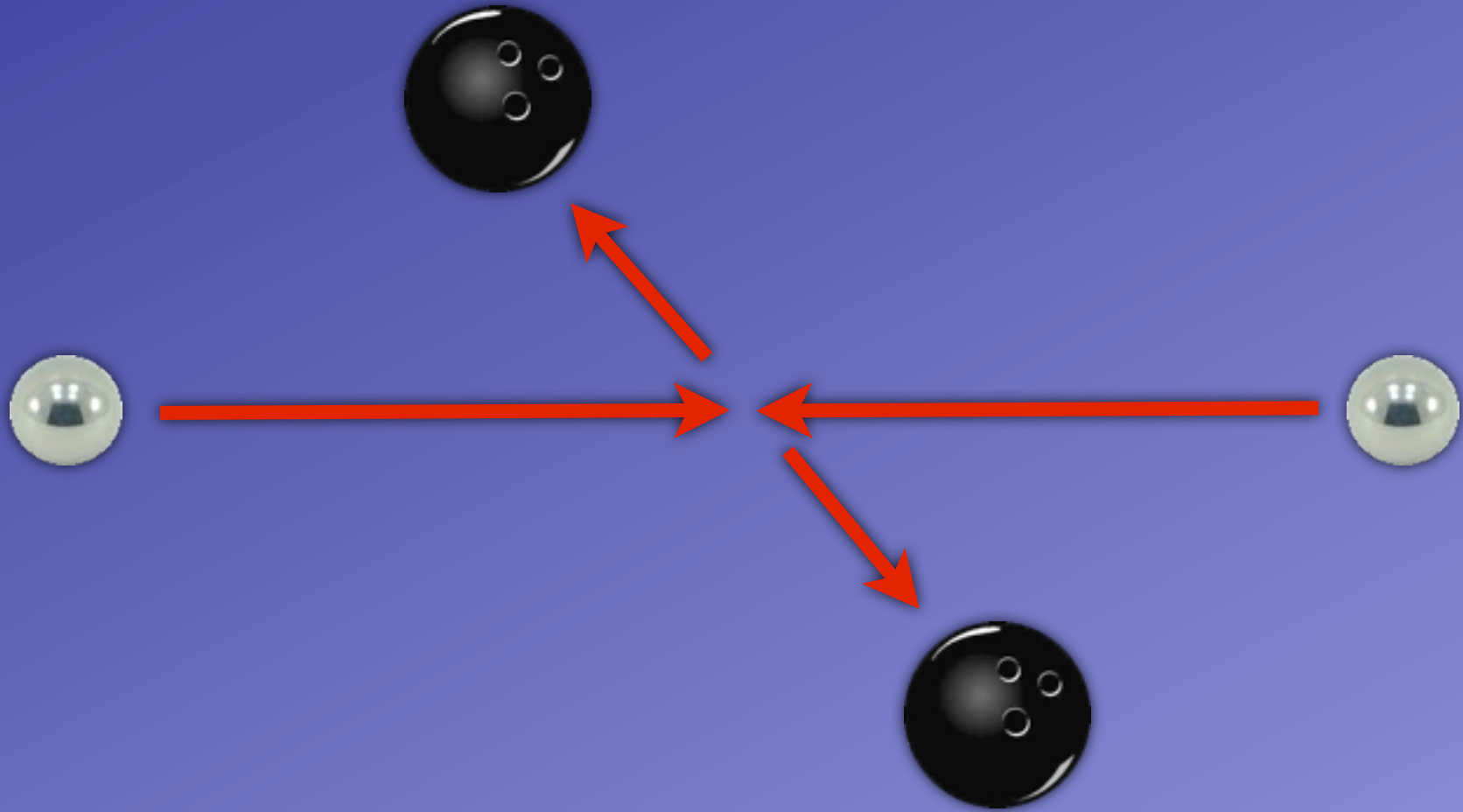


Inside the tunnel



Magnets

Why Collisions?....because $E=mc^2$



We are searching new high mass particles

We make them used $E=mc^2$

$E=mc^2$

Energy = mass * (speed of light)²



1 liter of water weighs
1 kg (2.2 lbs) at room
temperature

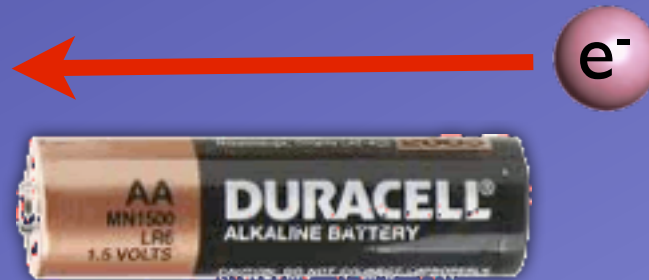


Just before boiling,
the same liter of
water weighs
3 nanograms more

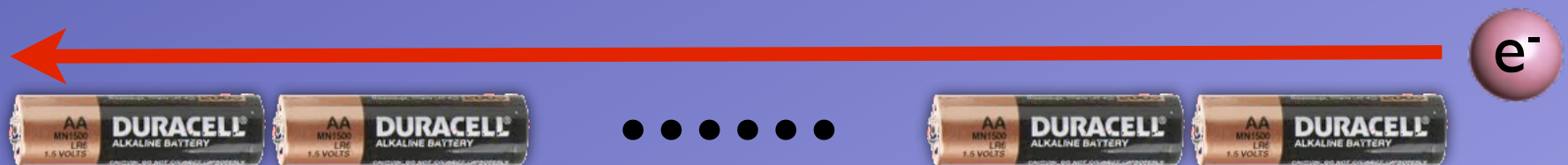
How high energy is the LHC?

Collision Energy is 8 TeV = 8 Trillion Electron Volts (eV)

1.5 eV = 1.5 “electron volts” is the energy an electron gains by going from one end of a AA battery to the other



8 TeV is the energy an electron would gain from lining up about 5.3 trillion AA batteries end-to-end

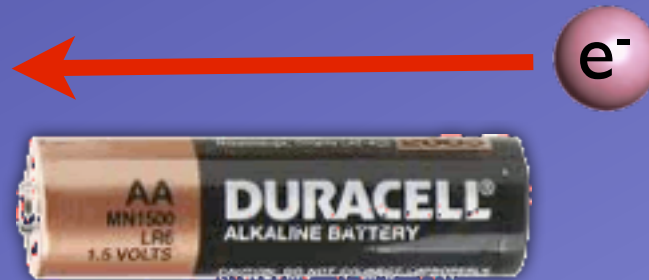


In 2015 we will increase the energy to 13 TeV

How high energy is the LHC?

Collision Energy is 8 TeV = 8 Trillion Electron Volts (eV)

1.5 eV = 1.5 “electron volts” is the energy an electron gains by going from one end of a AA battery to the other

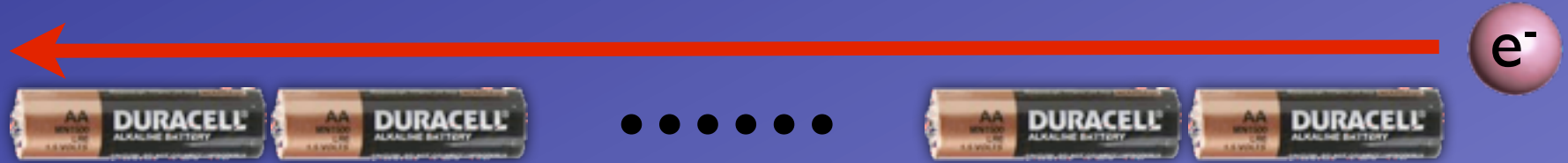


8 TeV is the energy an electron would gain from lining up about 5.3 trillion AA batteries end-to-end

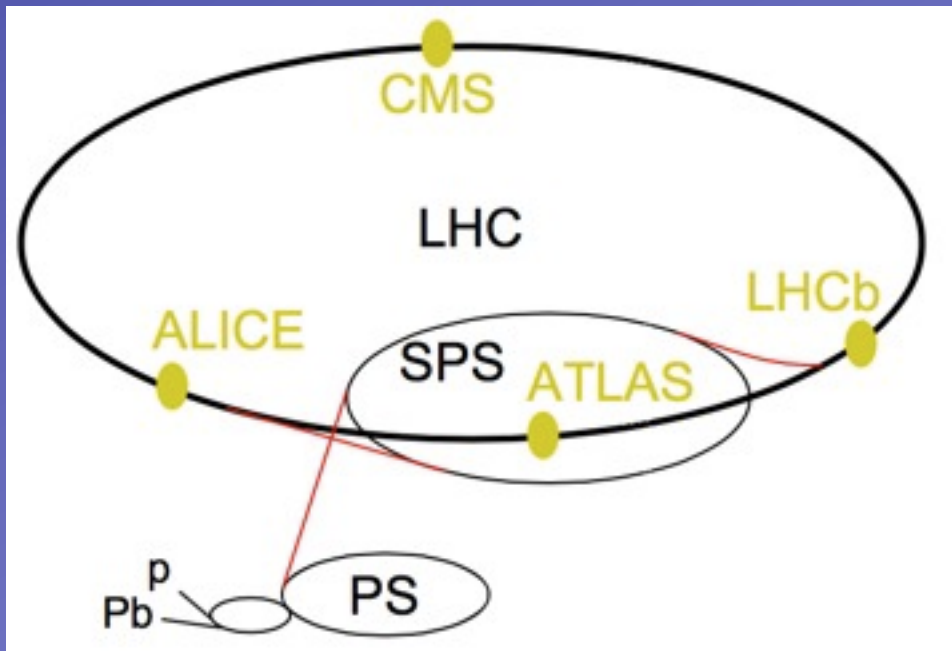
Making a proton takes 1 GeV

Making a Higgs takes 125 GeV =
1/64 of the beam energy

Why is the LHC a ring?



A line of 5.3 Trillion AA batteries would be 270,000,000 km long (almost twice the distance to the sun)



Protons travel around the circle 11,000 times per second

They accelerate to 8 TeV in about an hour

- gaining 200,000 eV per turn
- traveling a total distance that is 7.2 times the distance to the sun

Understanding the Energy Scale



In the ring we keep many (1380) bunches of about 100 billion protons each

- That is about **billionth of a grain of sand**



The beam has 70 megajoules of energy which is the kinetic energy of a **car moving 25 mph**

So the beam is a speck one billionth of grain of sand, that feels like car moving 25 mph to the beam stop (target where we put the beam when were done with it).

How data is collected...

Machine is Empty



How data is collected...

Machine is Empty

Turn Magnets on to Low Energy



How data is collected...

Machine is Empty

Turn Magnets on to Low Energy

Inject Proton Beam #1



How data is collected...

Machine is Empty

Turn Magnets on to Low Energy

Inject Proton Beam #1

Inject Proton Beam #2



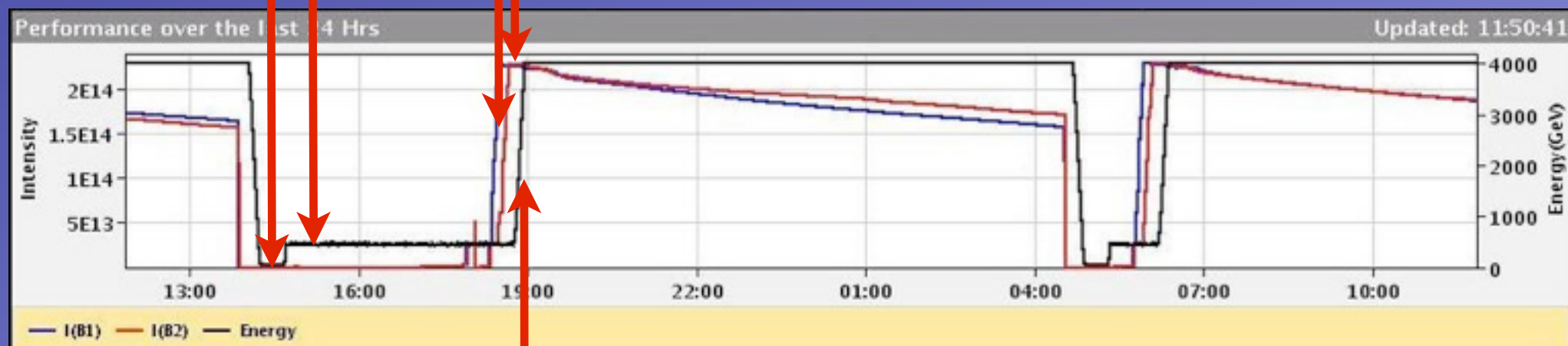
How data is collected...

Machine is Empty

Turn Magnets on to Low Energy

Inject Proton Beam #1

Inject Proton Beam #2



Ramp Energy

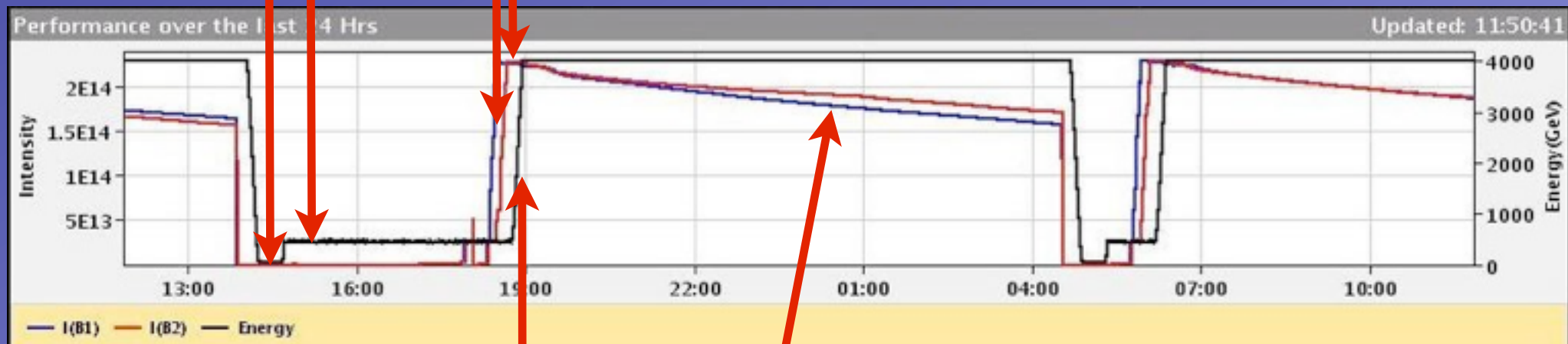
How data is collected...

Machine is Empty

Turn Magnets on to Low Energy

Inject Proton Beam #1

Inject Proton Beam #2



Ramp Energy

Slow Decline in Beam Intensity

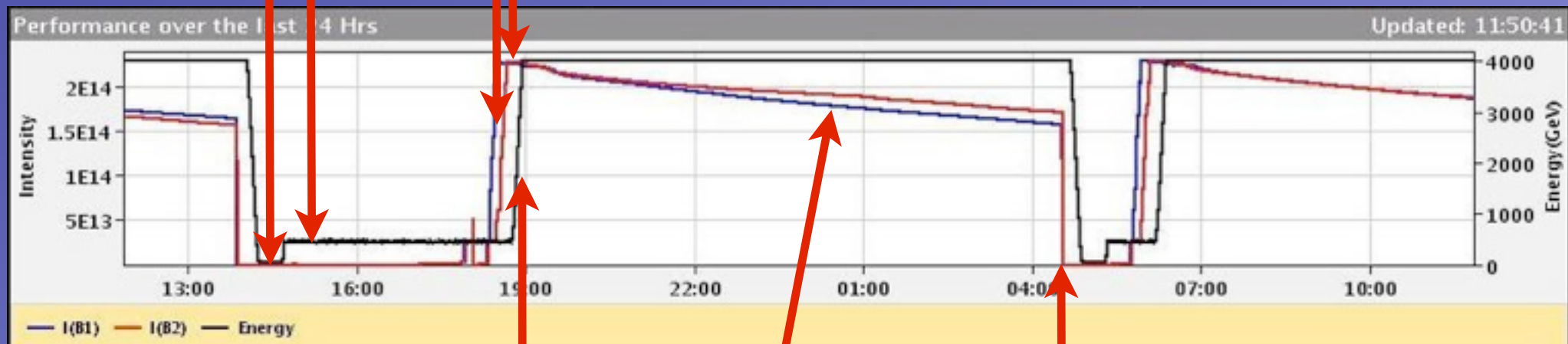
How data is collected...

Machine is Empty

Turn Magnets on to Low Energy

Inject Proton Beam #1

Inject Proton Beam #2



Ramp Energy

Slow Decline in Beam Intensity

Dump Beams

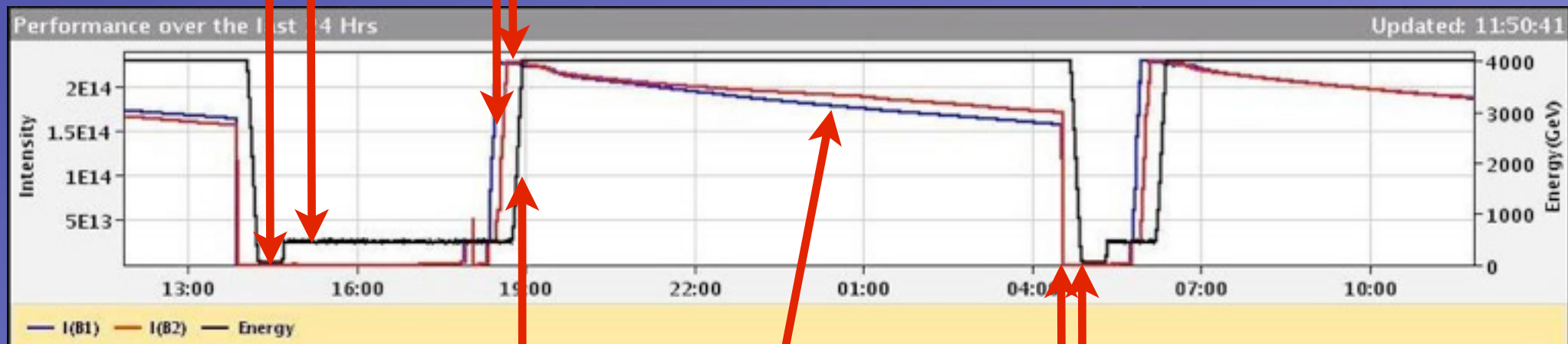
How data is collected...

Machine is Empty

Turn Magnets on to Low Energy

Inject Proton Beam #1

Inject Proton Beam #2



Ramp Energy

Slow Decline in Beam Intensity

Dump Beams

Turn off Magnets

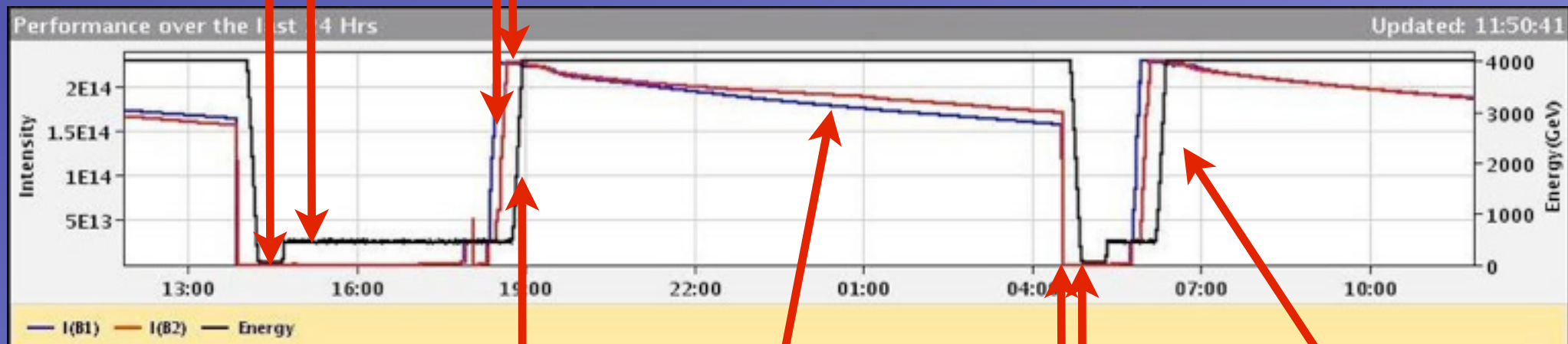
How data is collected...

Machine is Empty

Turn Magnets on to Low Energy

Inject Proton Beam #1

Inject Proton Beam #2



Ramp Energy

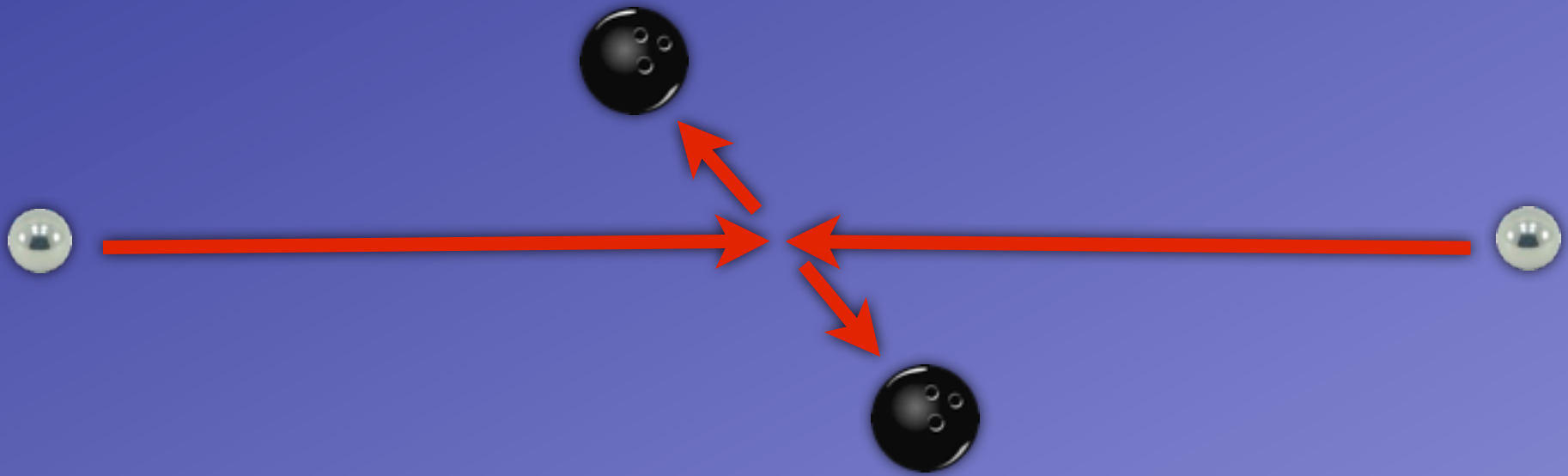
Slow Decline in Beam Intensity

Dump Beams

Turn off Magnets

And then repeat...

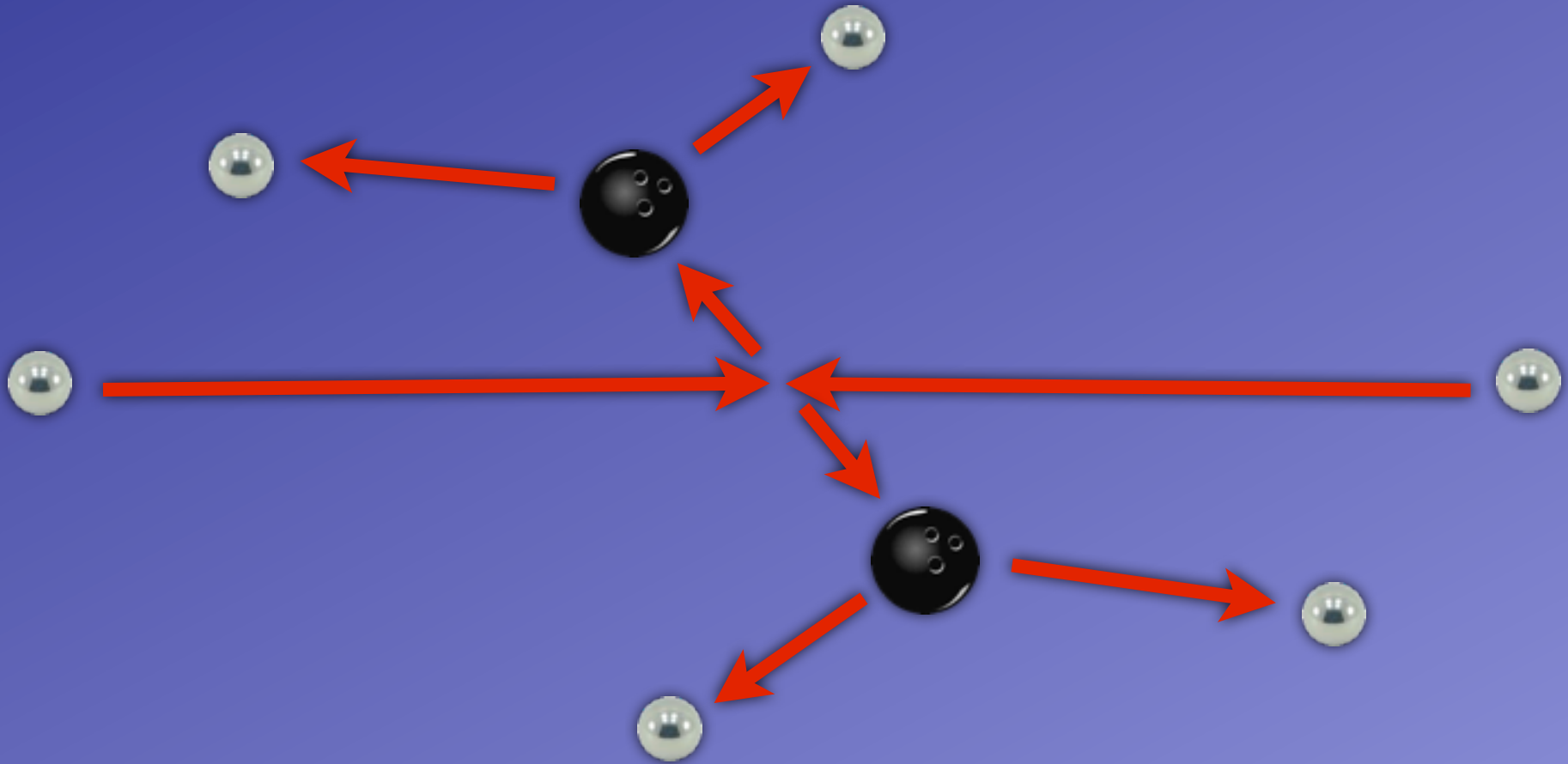
Back to $E=mc^2$



Remember, we are colliding pinballs to make bowling balls

But, $E=mc^2$ goes the other direction too....

Back to $E=mc^2$

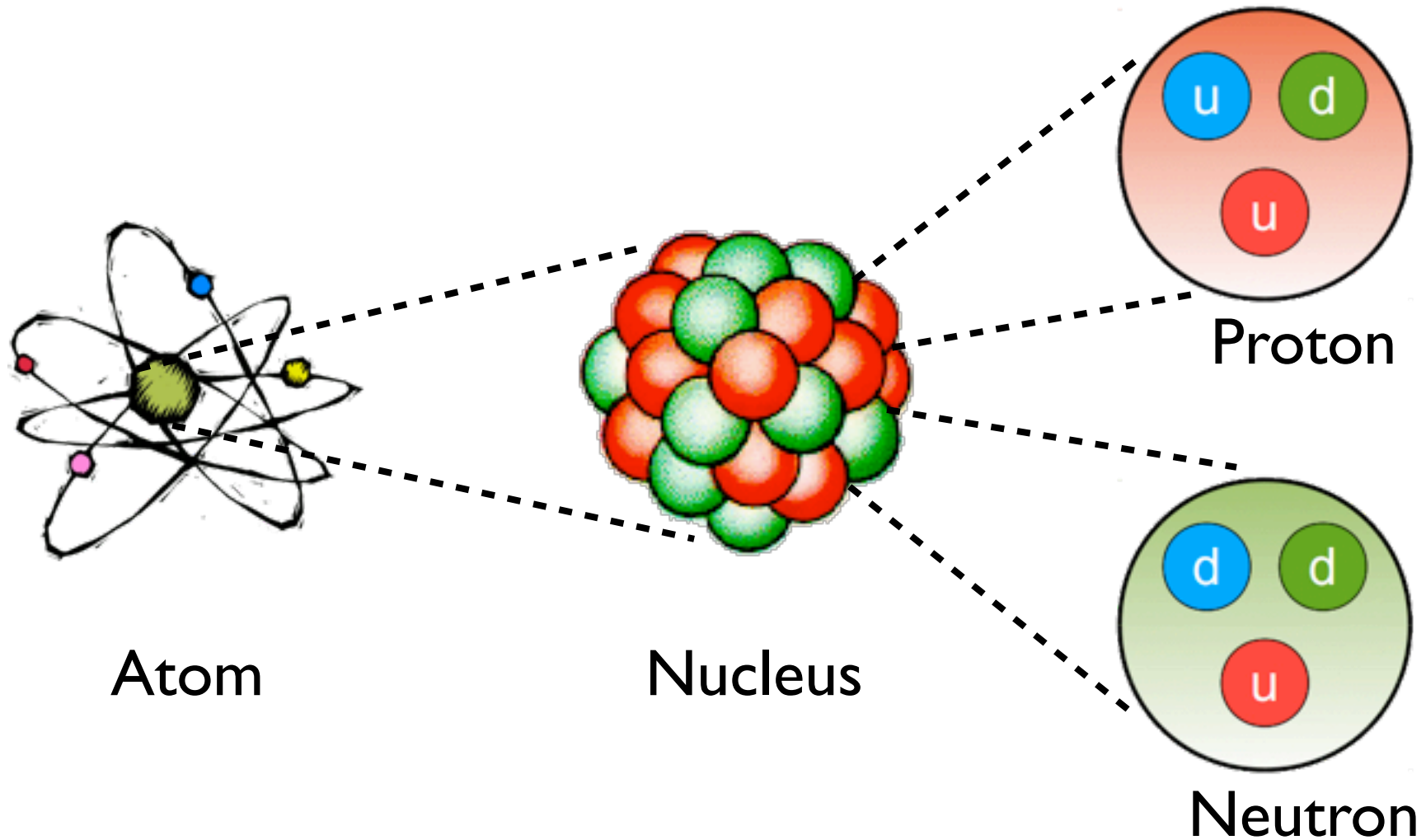


Remember, we are colliding pinballs to make bowling balls

But, $E=mc^2$ goes the other direction too...

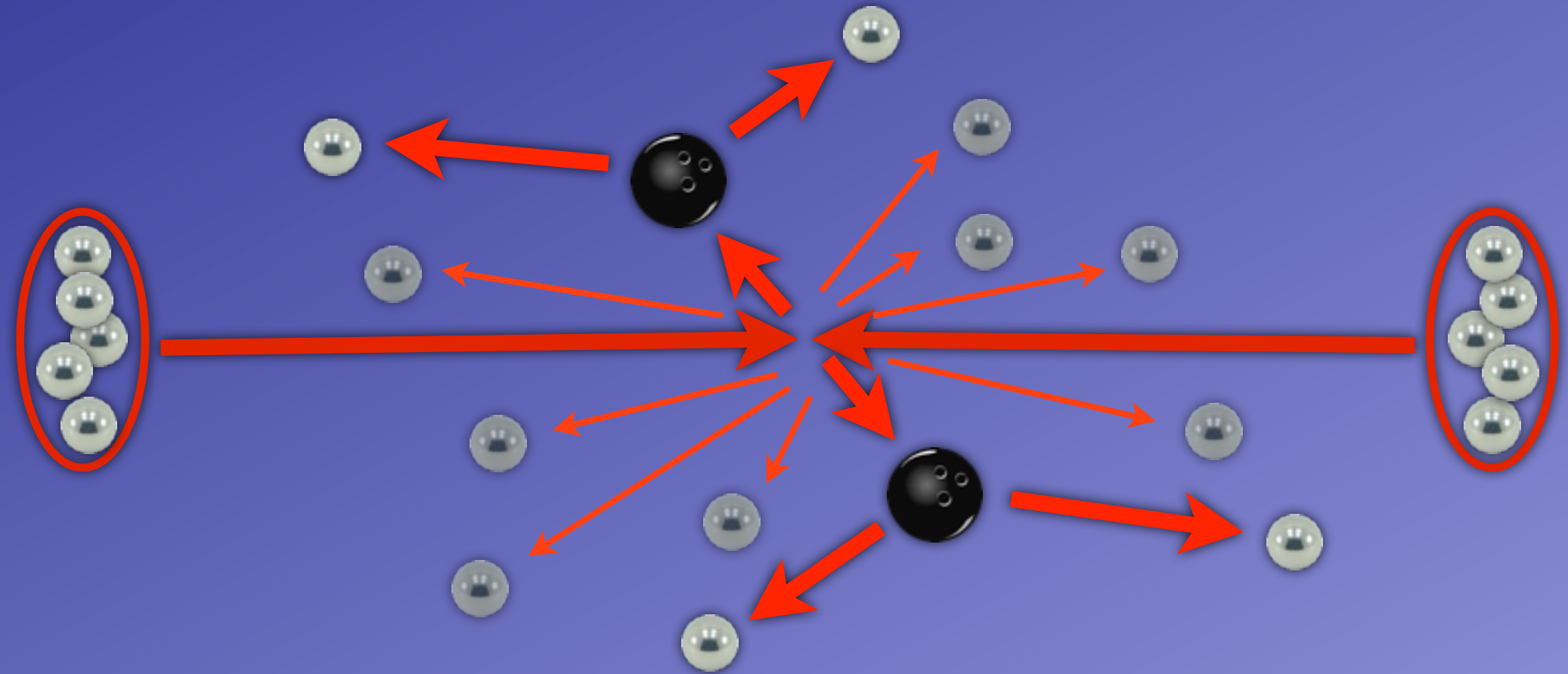
The new massive particles very quickly
“decay” back to lighter particles

One More Complication



The proton not just one particle!

Back to $E=mc^2$

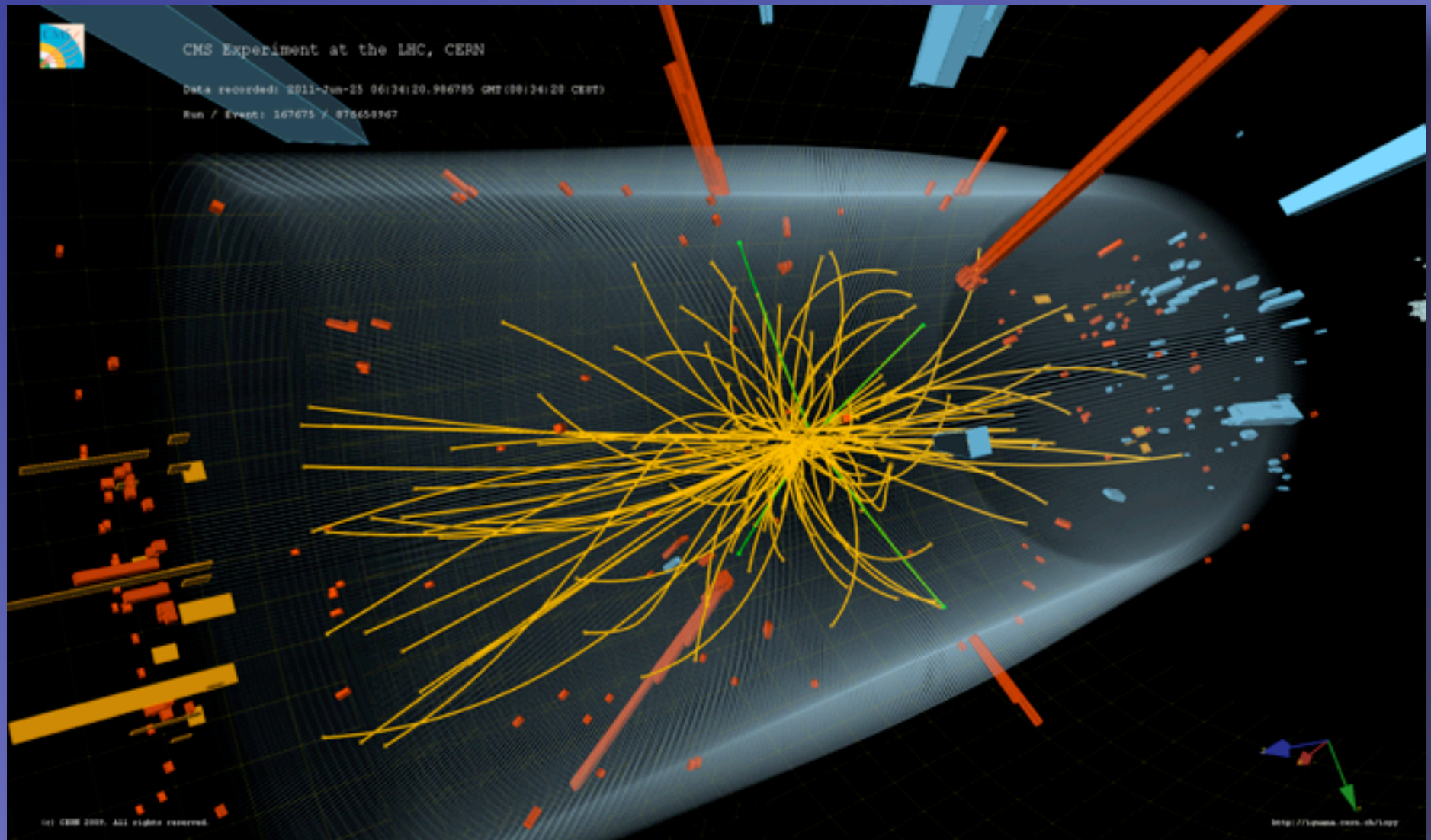


Protons are really a sack of particles

Get lots of collisions in addition to the interesting one

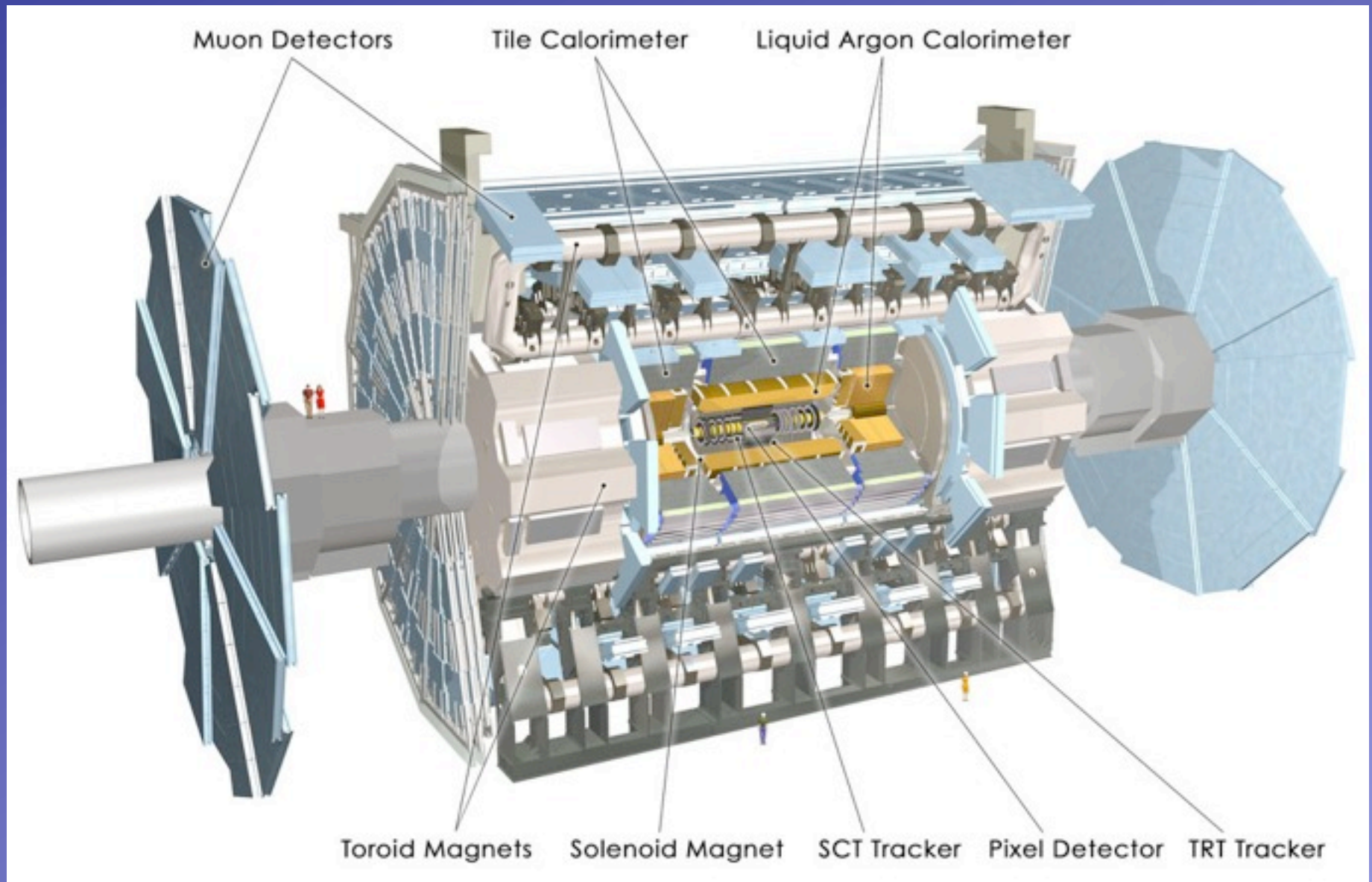
The particles from the high mass particles
tend to have larger energies

A real collision



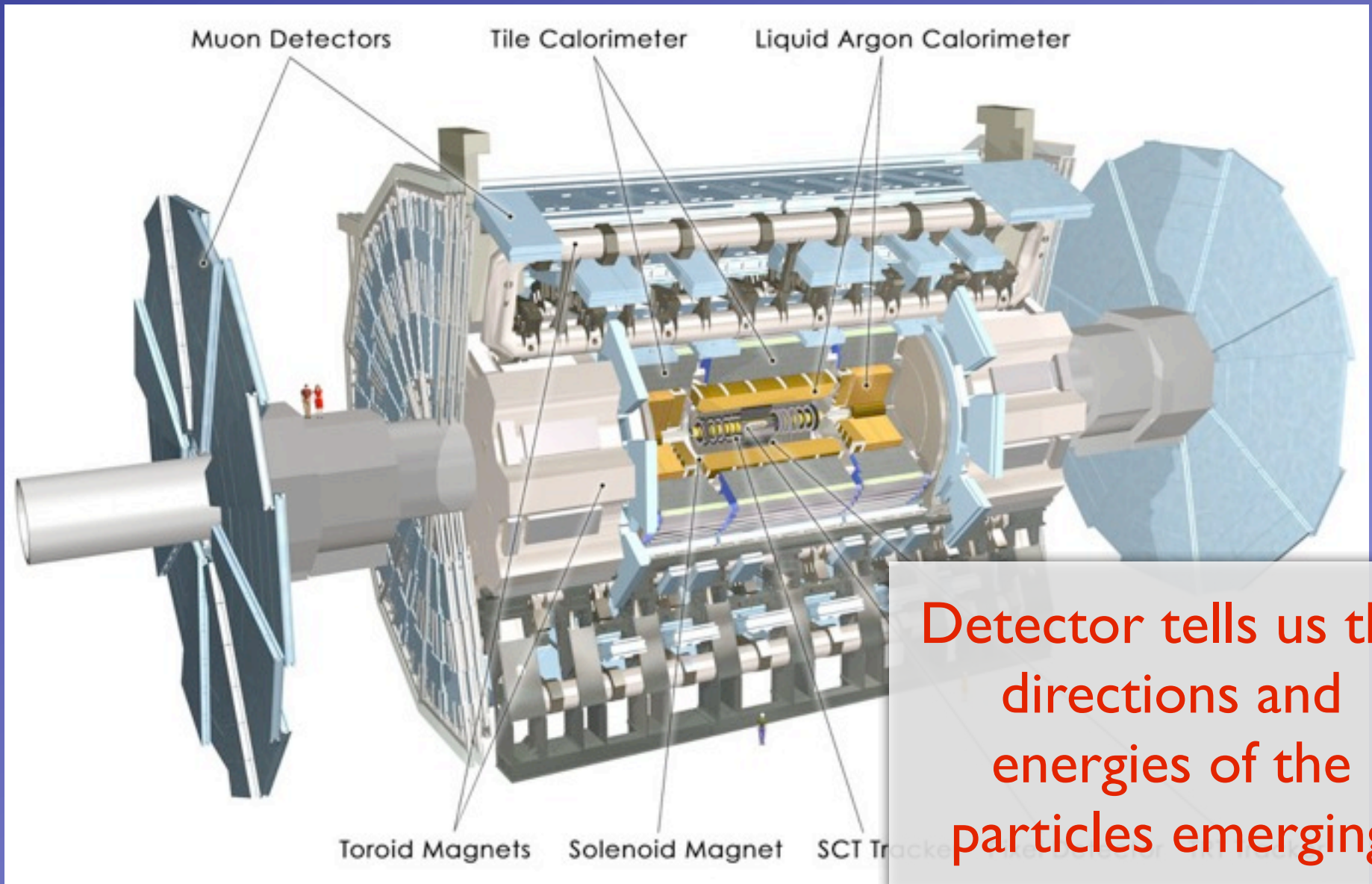
A spray of particles emerges from the collision
We have to measure as much about it as we can....

Detectors



Detector is like a camera which takes pictures of the collisions

Detectors

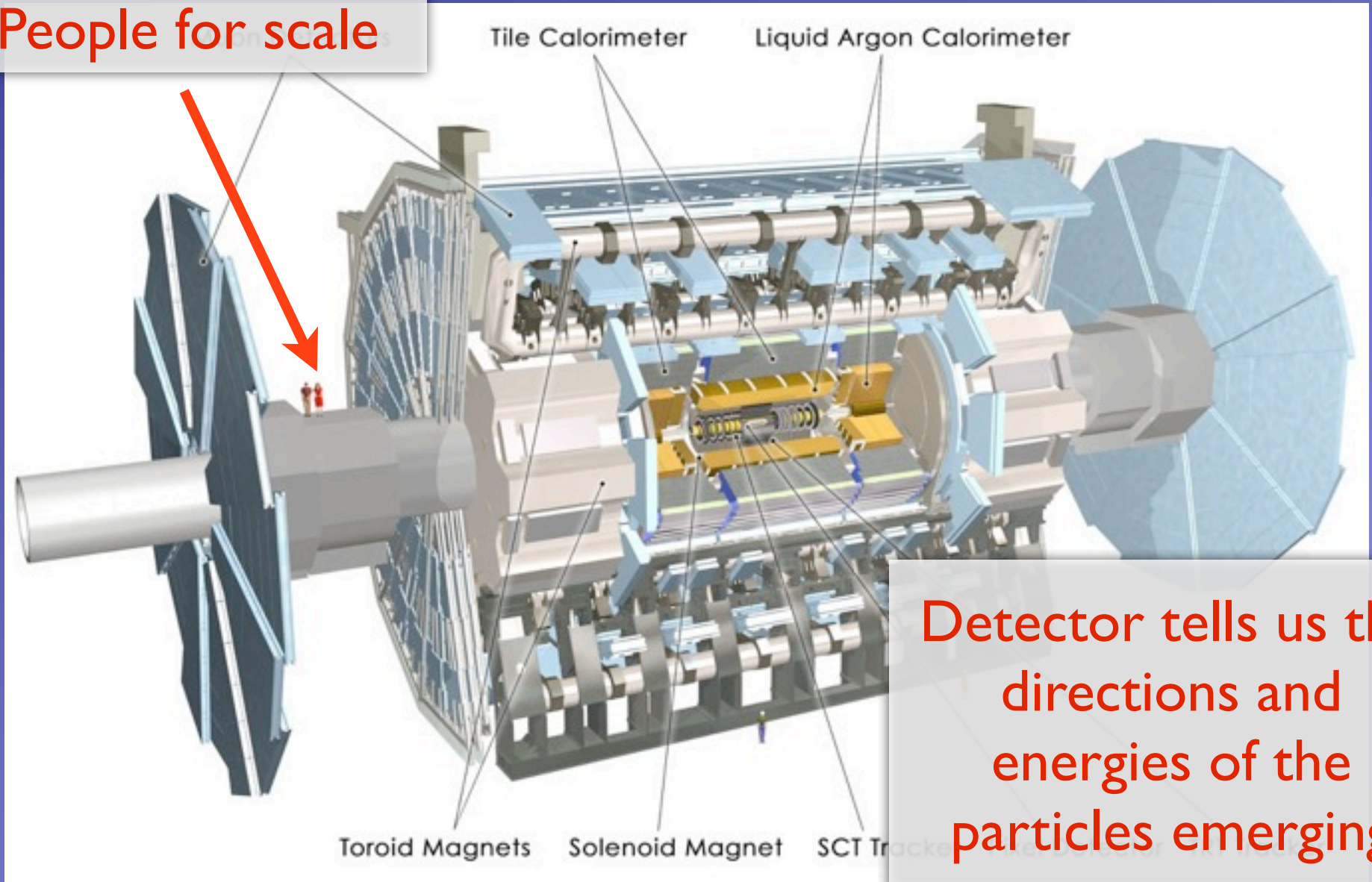


Detector tells us the directions and energies of the particles emerging

Detector is like a camera which takes pictures of the collisions

Detectors

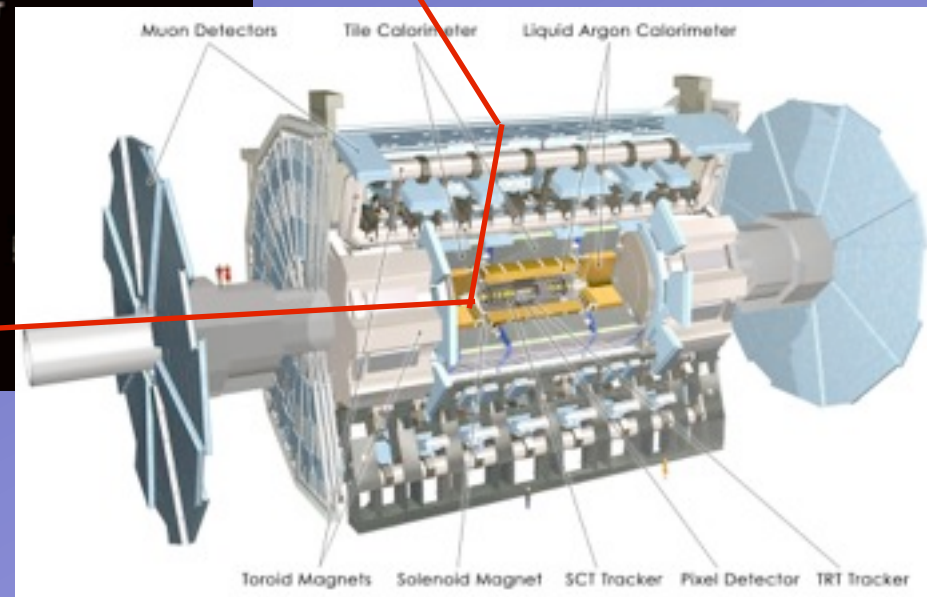
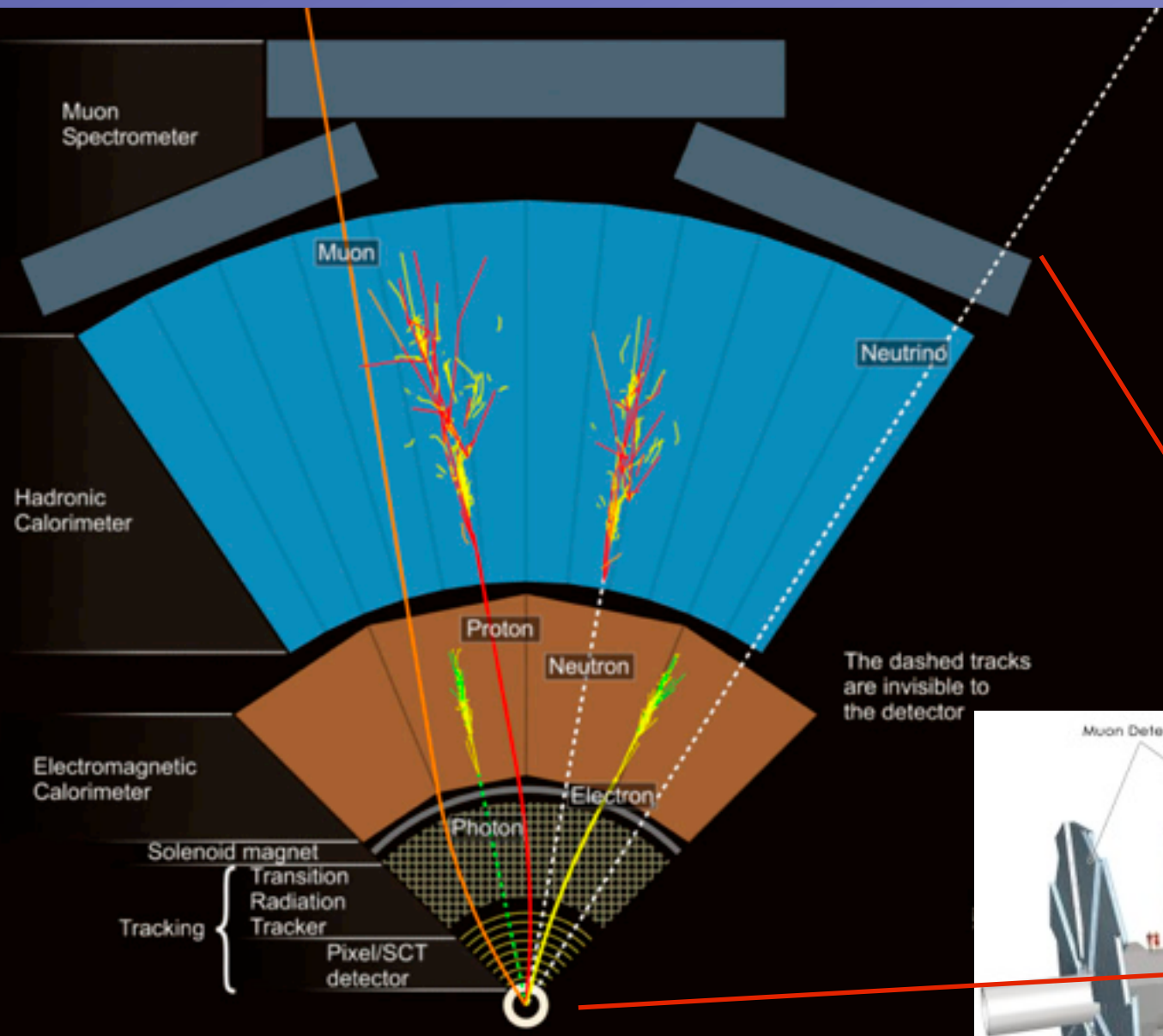
People for scale



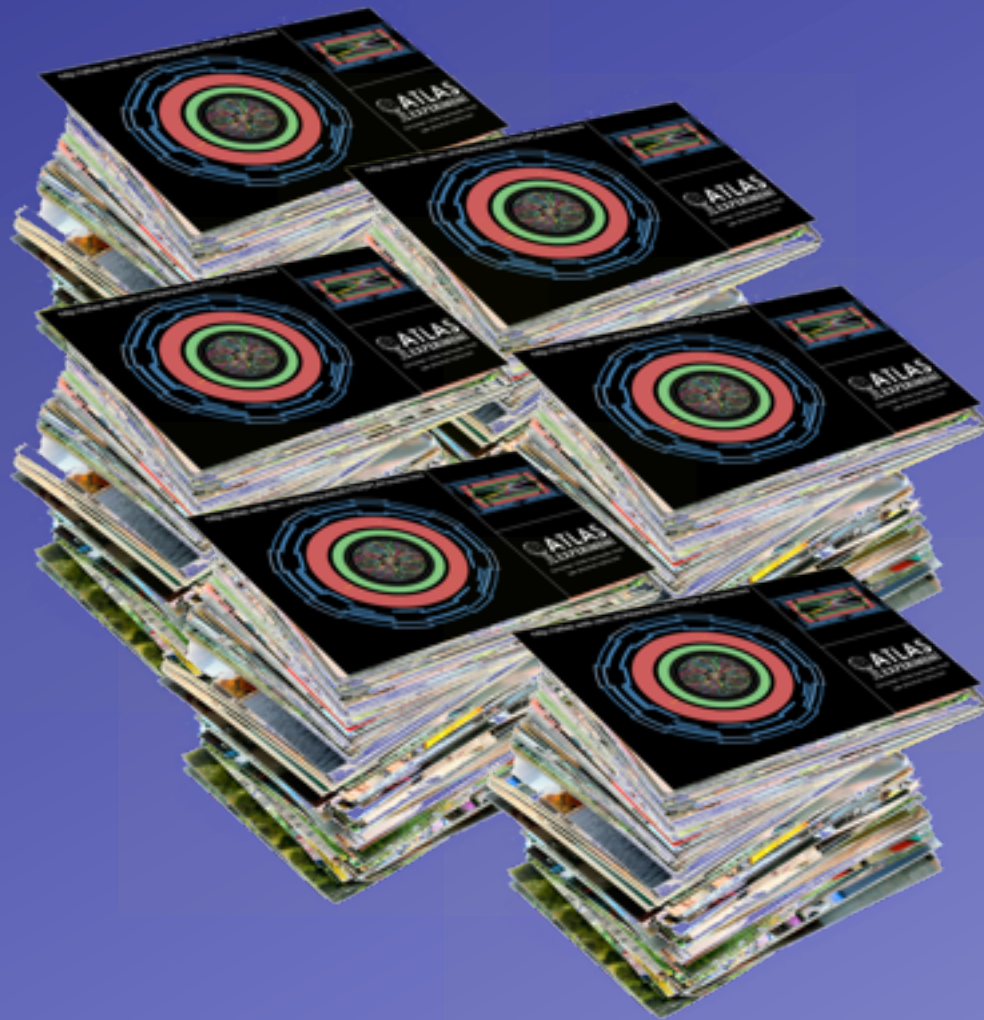
Detector tells us the directions and energies of the particles emerging

Detector is like a camera which takes pictures of the collisions

Different Particles in the Detector

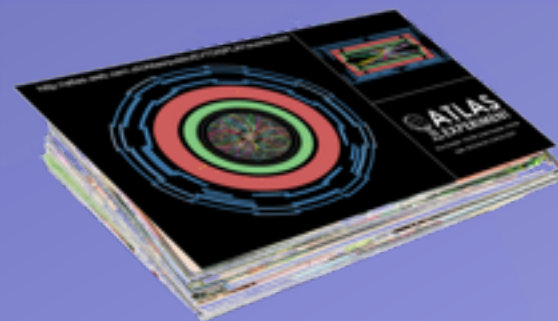


Triggering



ATLAS makes 20 million pictures (“events”) per second

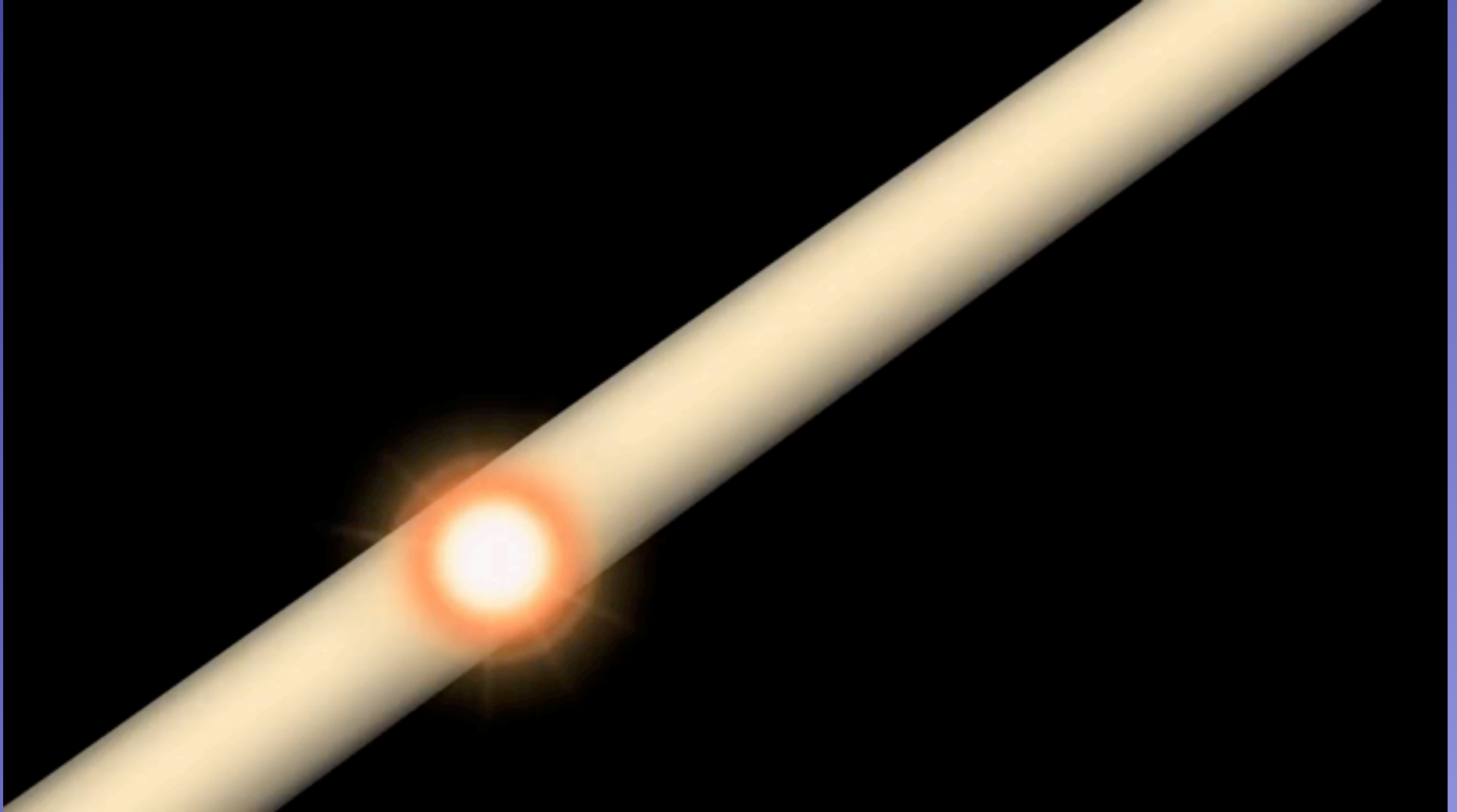
Trigger makes the difficult choice of what to keep



We can afford to store only 400 of those

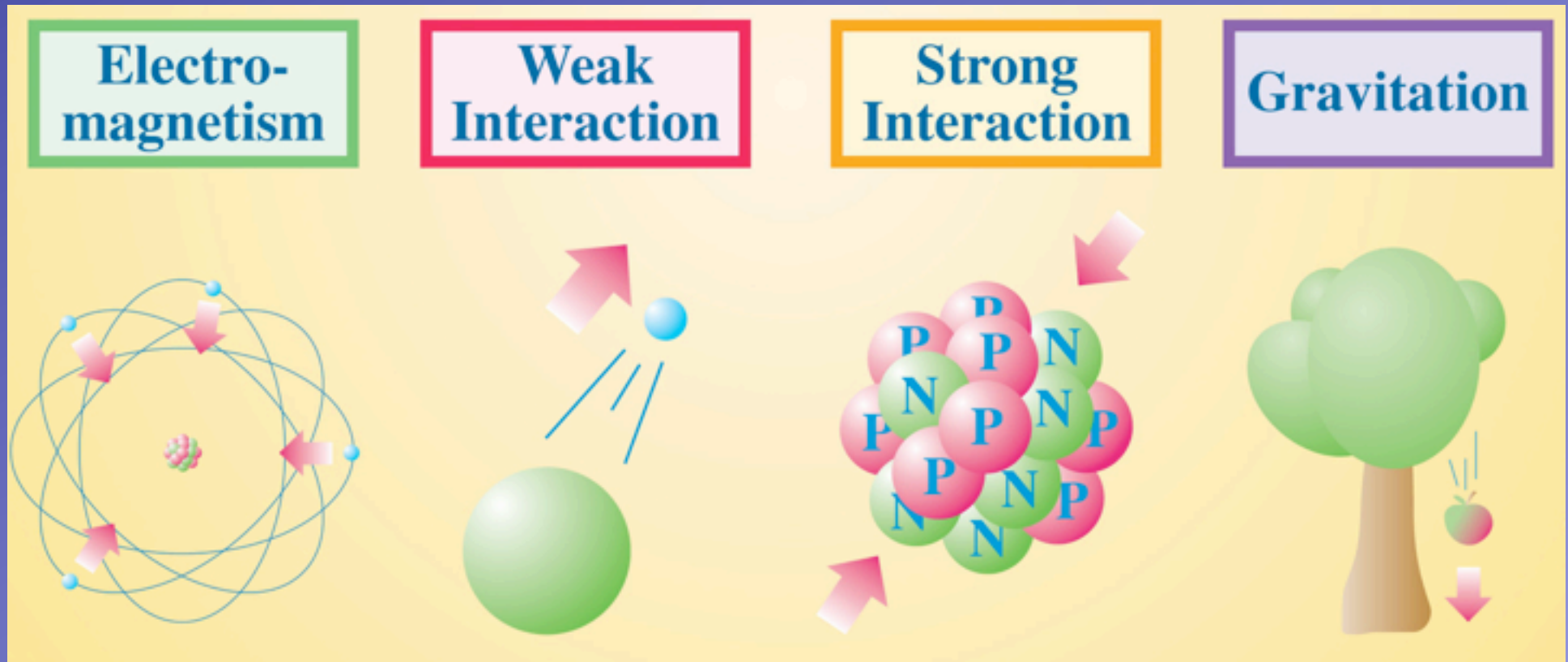
Summary Video

Summary Video



What we are searching for...

Fundamental Forces of Nature and the Role the Higgs Plays



The Fundamental Forces

Electricity and Magnetism (EM)

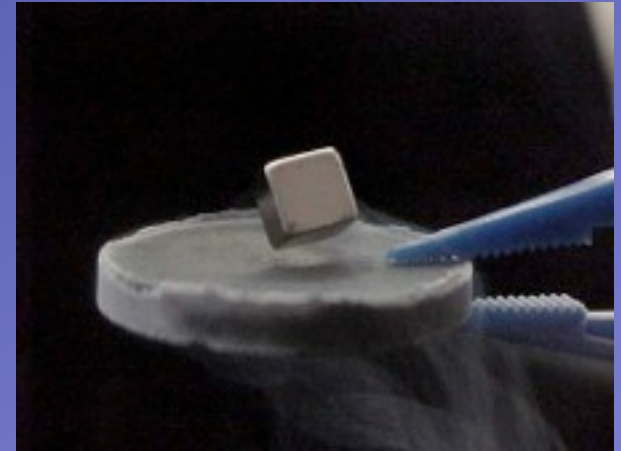
Pretty much all the “forces” in everyday life other than gravity



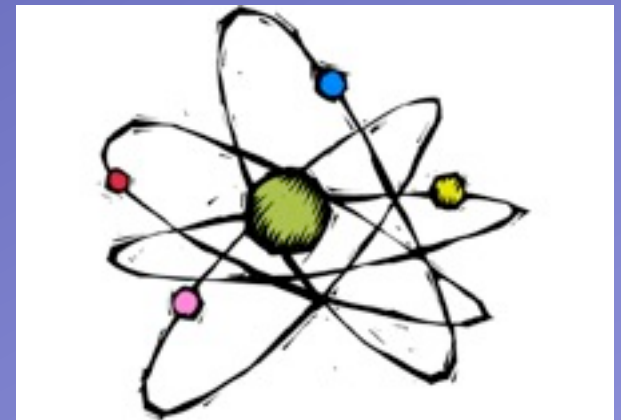
My feet on the floor

- Gravity pulls me down
- EM holds me up

Magnets



The Atom
...and most of chemistry



Light



The Fundamental Forces

Electricity and Magnetism (EM)

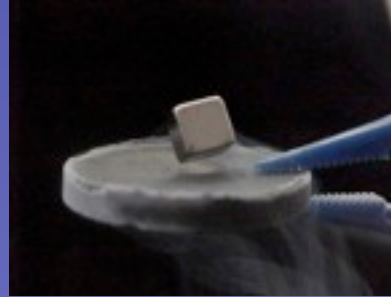


My feet on the floor

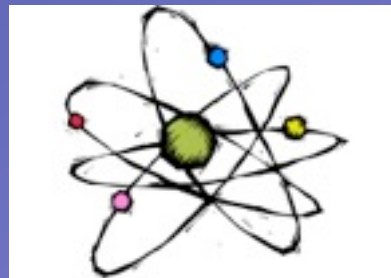
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- EM holds me up

Pretty much all the “forces” in everyday life other than gravity

Magnets



The Atom



Light



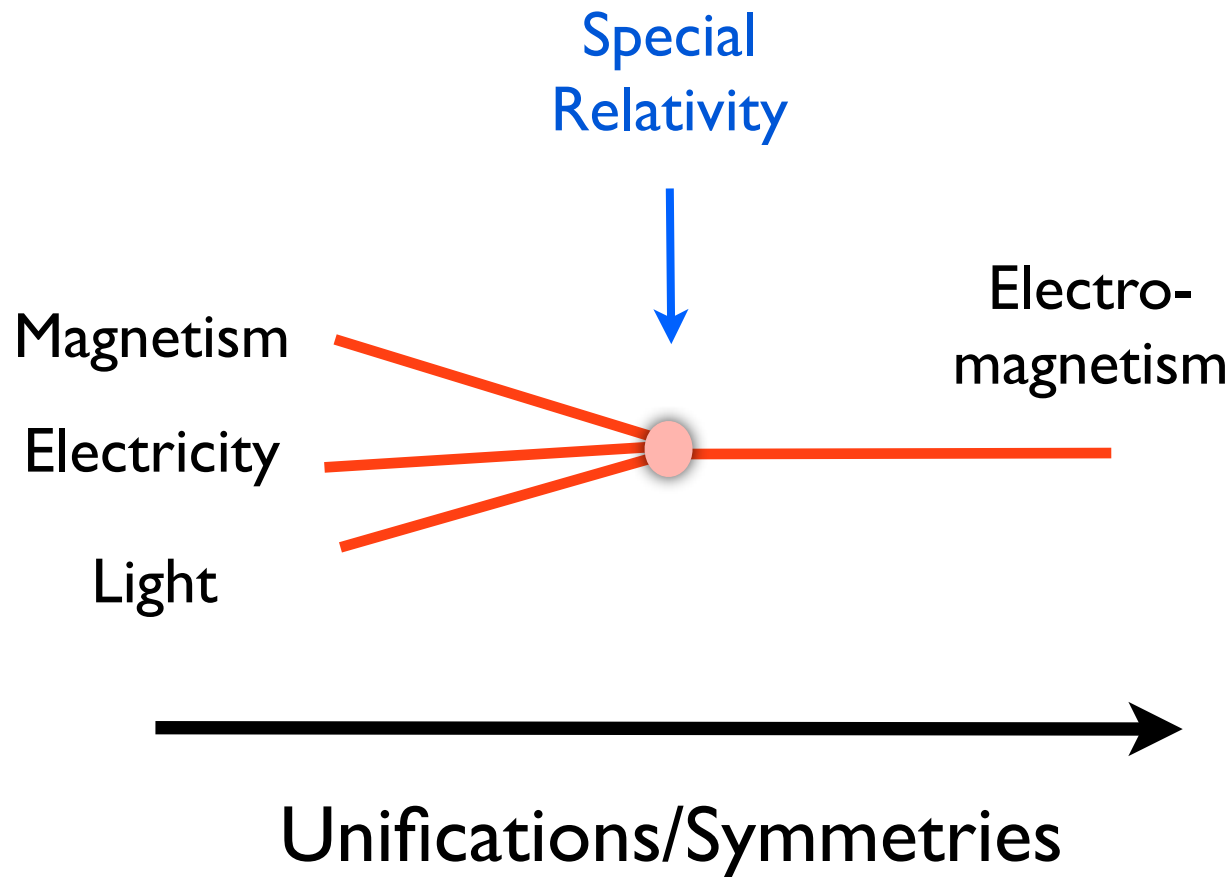
You might be amazed to learn all these things can be described by just one force

This is one of the goals of physics!

Unification and symmetry play a central role

The Fundamental Forces

Electricity and Magnetism (EM)



*Special Relativity is a symmetry
between space and time*

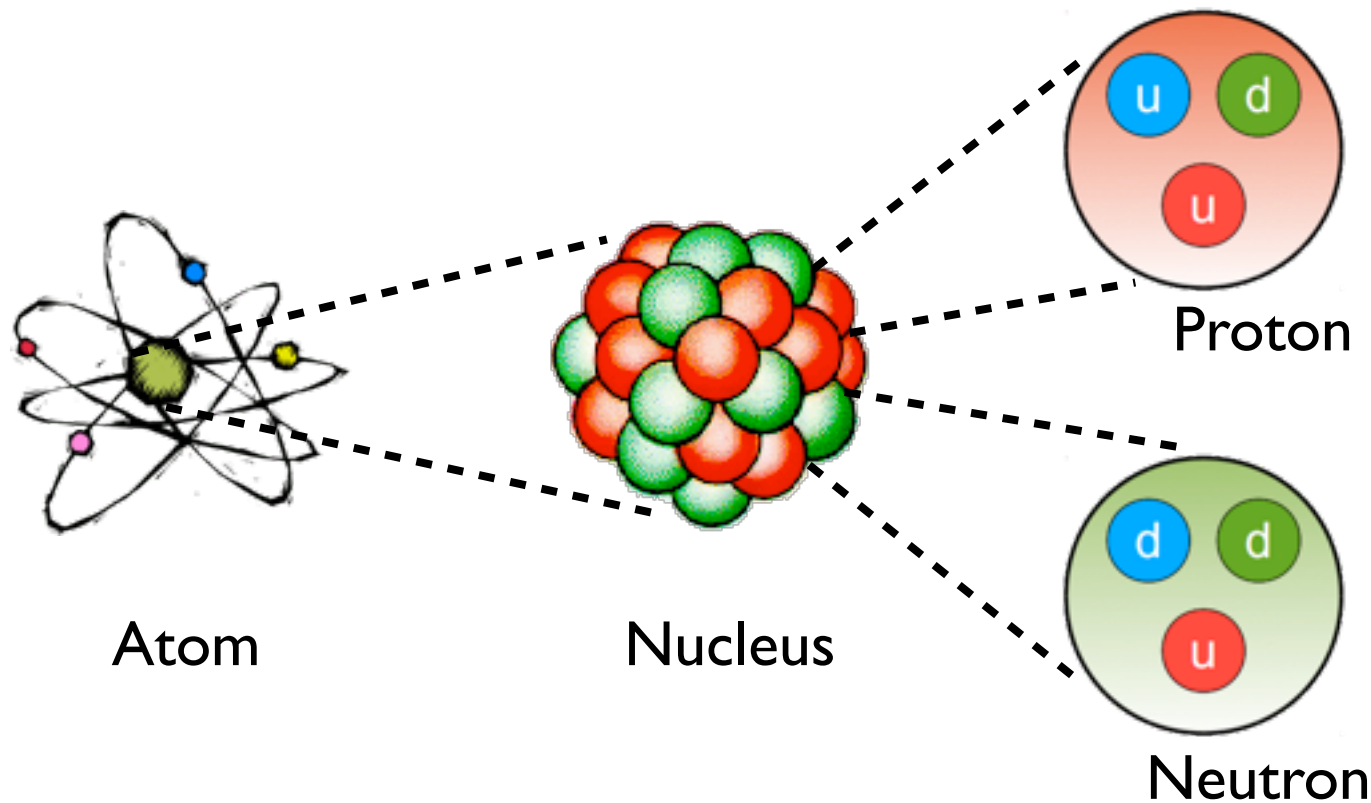
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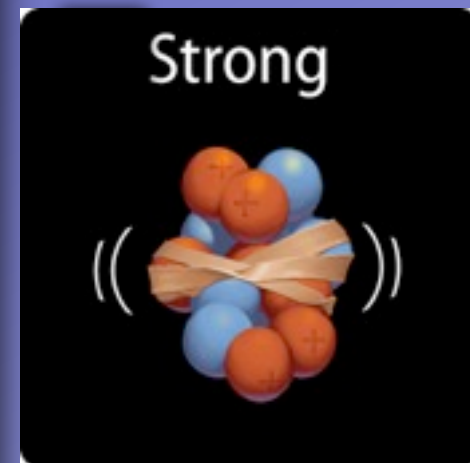
Unification and symmetry play a central role

The Fundamental Forces

The Strong Force



*This is what
holds the
nucleus
together*

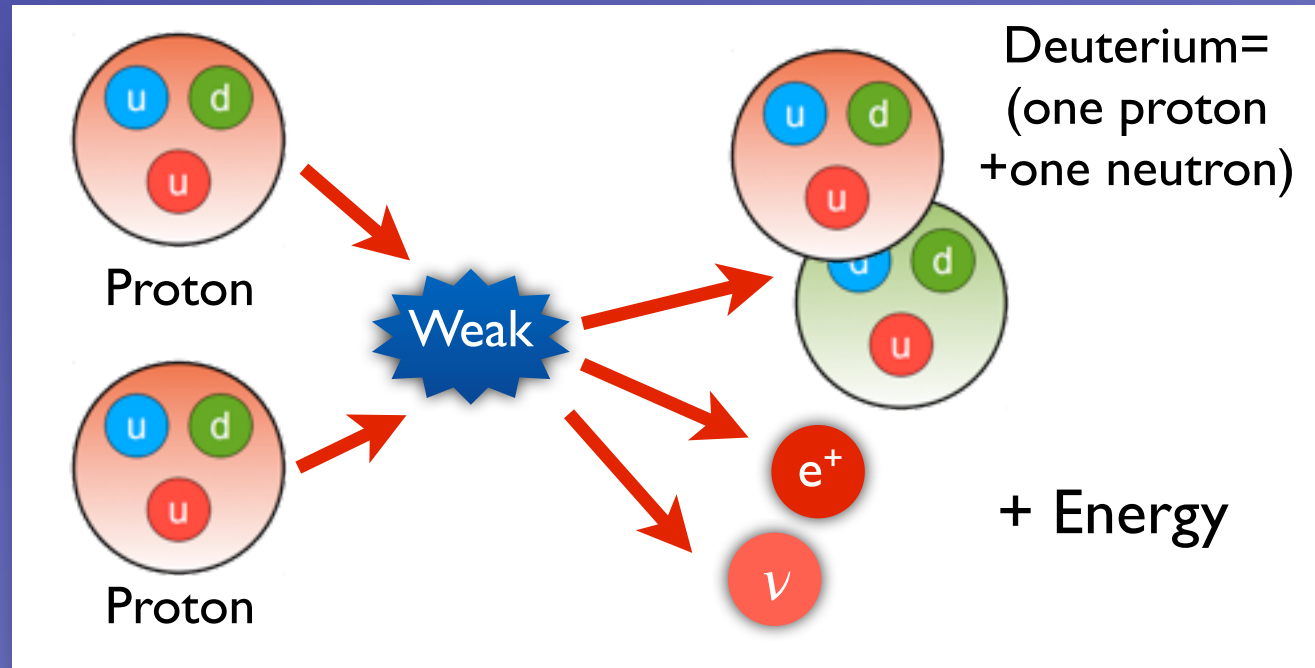


The nucleus is about 10^5 times smaller than an atom...
hence the name “strong force”

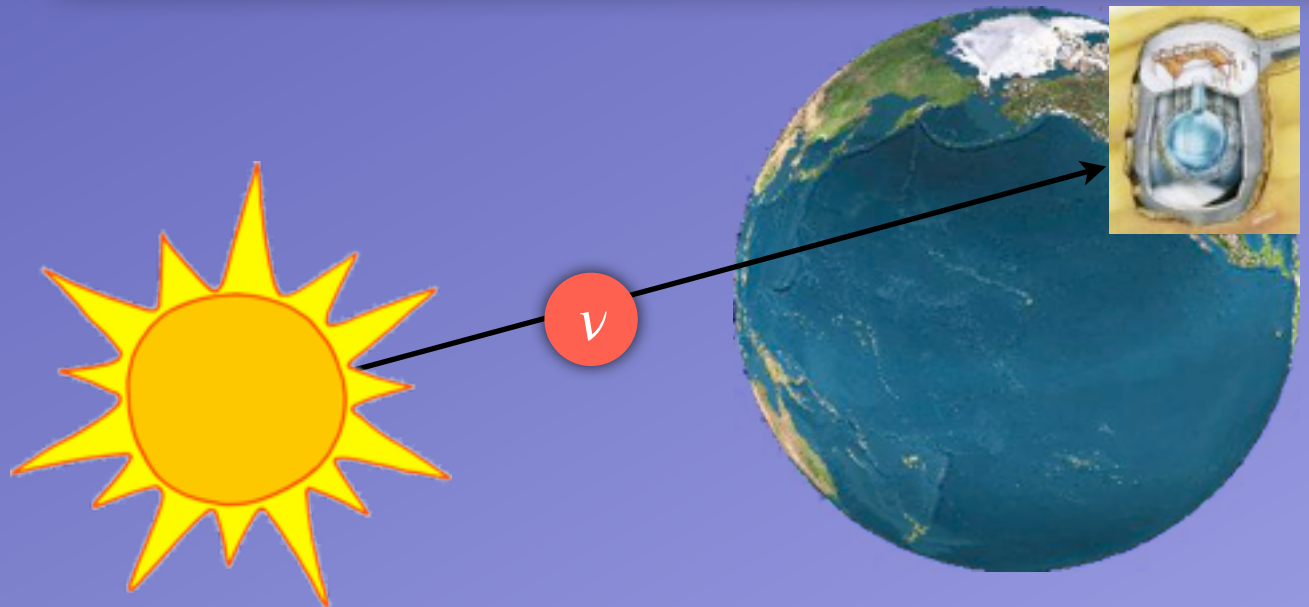
The Fundamental Forces

The Weak Force

The Weak Force is part of the burning of protons in the sun



The Neutrino ν only interacts weakly and will pass right through earth



The Fundamental Forces

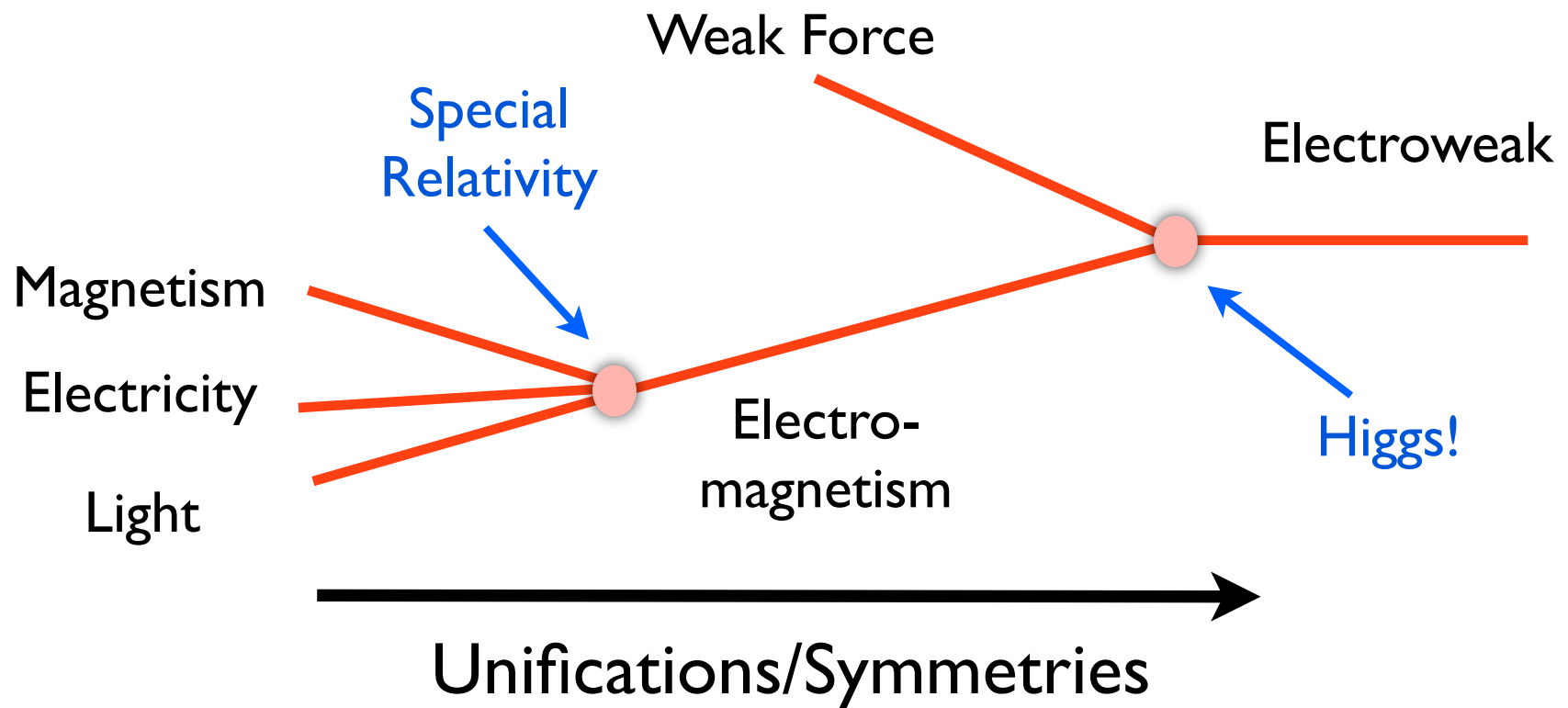
Gravity

We don't have a theory for how gravity works on very small scales. I.e. very very close to the electron



E.g. if instead of the LHC I had a Very Very Large Hadron Collider, 10^{16} times larger, gravity would matter, but we don't know how to calculate it

The Higgs



Symmetry is really when we realize the two things are manifestations of the same thing

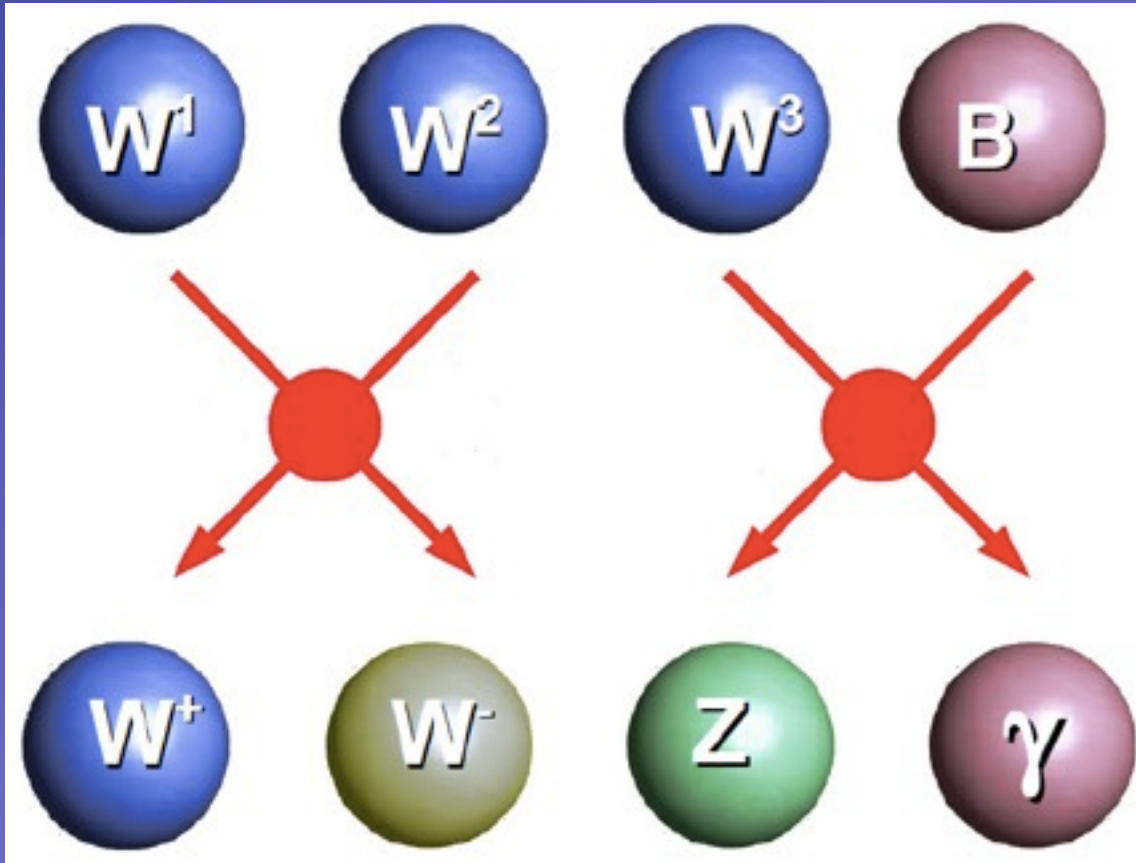
The Higgs does a funny job of breaking a symmetry

The Weak and Electromagnetic Forces seem different but they secretly the same

Symmetry Breaking

Before symmetry breaking :

3 identical + 1 other force carriers



Predicts relationships between....

W and Z masses, and strength of the weak and electromagnetic forces

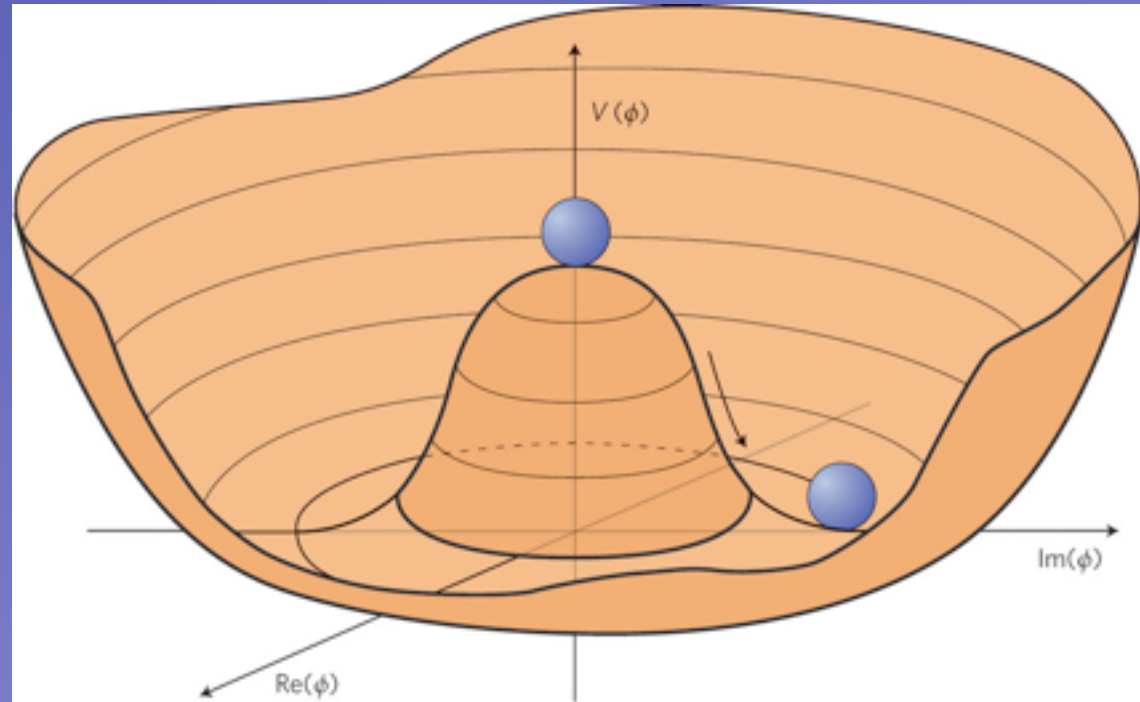
After symmetry breaking:

4 different kinds of force carriers

Higgs and Mass

Higgs breaks symmetry between Electromagnetism and Weak force by giving things mass

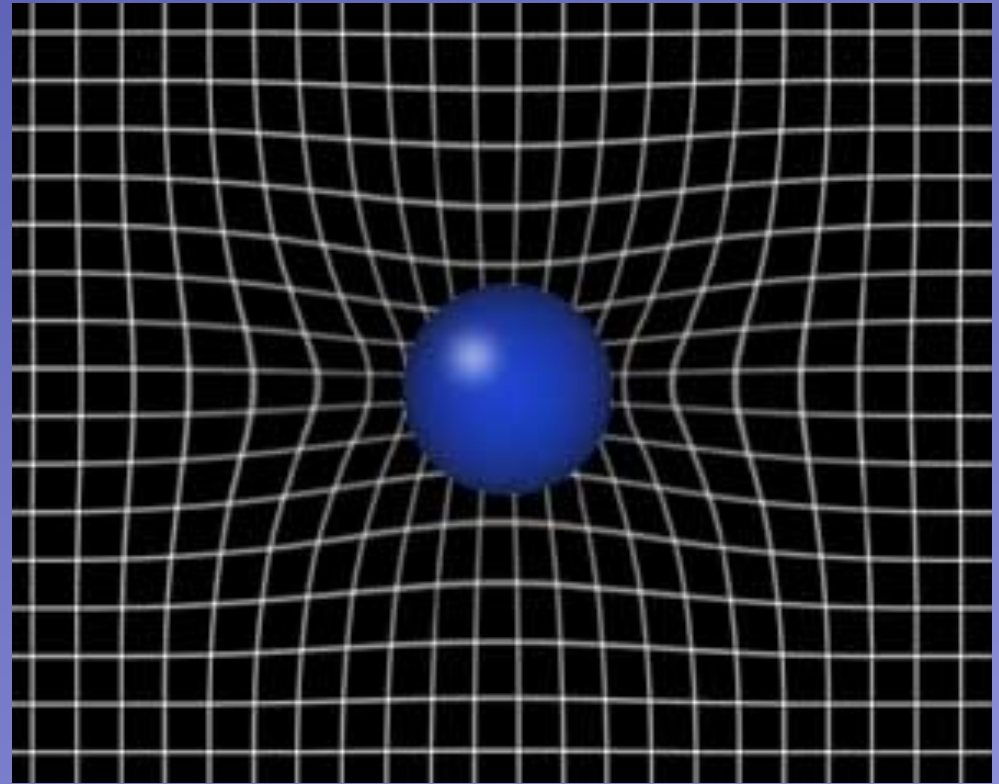
- It takes more energy to have no Higgs field
- Think of Higgs field like the electric field... it has a value at every point



Higgs and Mass

Higgs breaks symmetry between Electromagnetism and Weak force by giving things mass

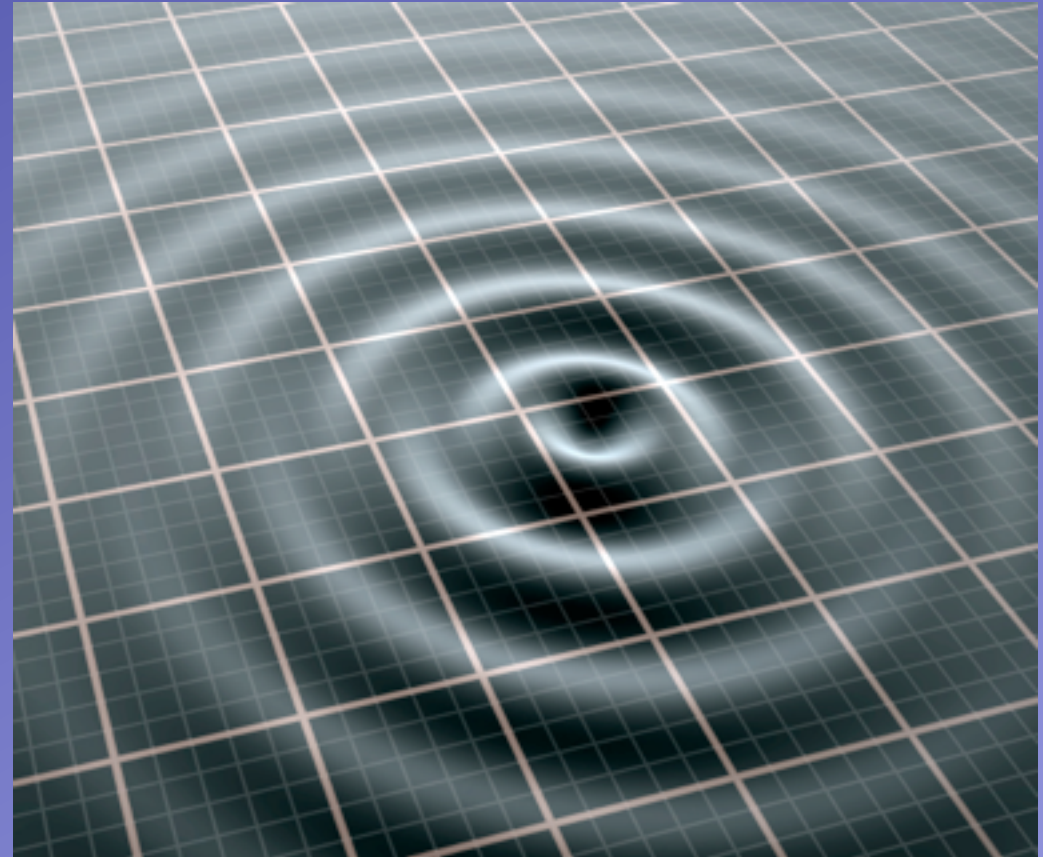
- It takes more energy to have no Higgs field
- The Higgs field is everywhere
- When a particle “couples” to the Higgs it takes energy to displace the Higgs field
- $E=mc^2$... particles get mass



Higgs and Mass

Higgs breaks symmetry between Electromagnetism and Weak force by giving things mass

- It takes more energy to have no Higgs field
- The Higgs field is everywhere
- When a particle “couples” to the Higgs it takes energy to displace the Higgs field
- $E=mc^2$... particles get mass



Higgs Particle is a wave in the Higgs field

Hard to Find

Why was the Higgs so hard to find?

The Problem:

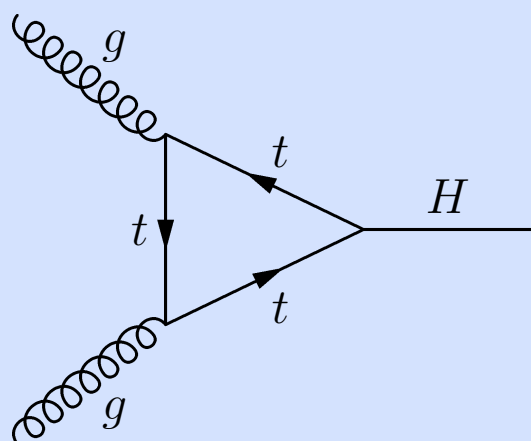
- 1) Particles that couple well to the Higgs are heavy
- 2) Heavy particles decay fast
- 3) We can only collide particles stable enough to put them in an accelerator

Hard to Find

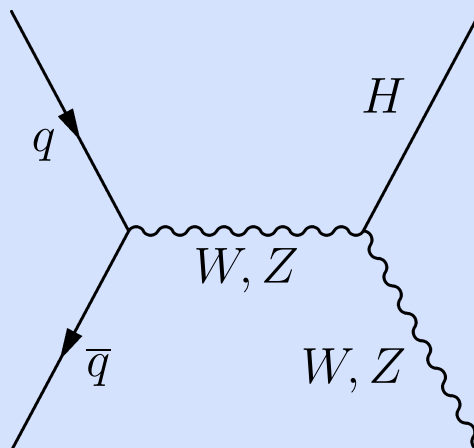
Why was the Higgs so hard to find?

The Solution:

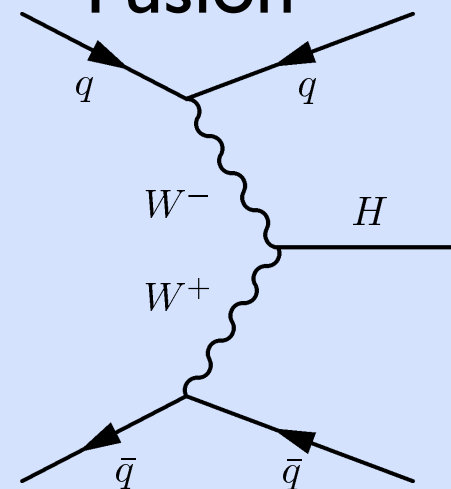
Gluon Fusion



Associated Production



Vector Boson Fusion



These are not allowed in classical physics...
but quantum mechanics lets them happen at
small rates (so we need lots of data)

The Higgs Discovery

Quantum Mechanics is probabilistic

- The Higgs can decay into many different things
- The Higgs has been seen in....

- $H \rightarrow \gamma\gamma$ (in “other”)

- $H \rightarrow ZZ$

- $H \rightarrow WW$

- Still searching in ...

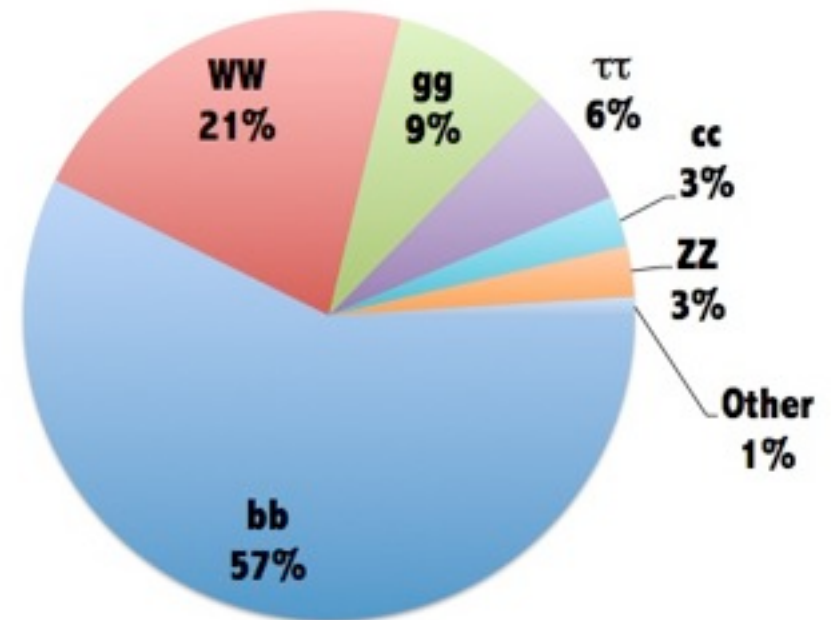
- $H \rightarrow \tau\tau$

- $H \rightarrow b\bar{b}$

- $H \rightarrow \mu\mu$ (in “other”)

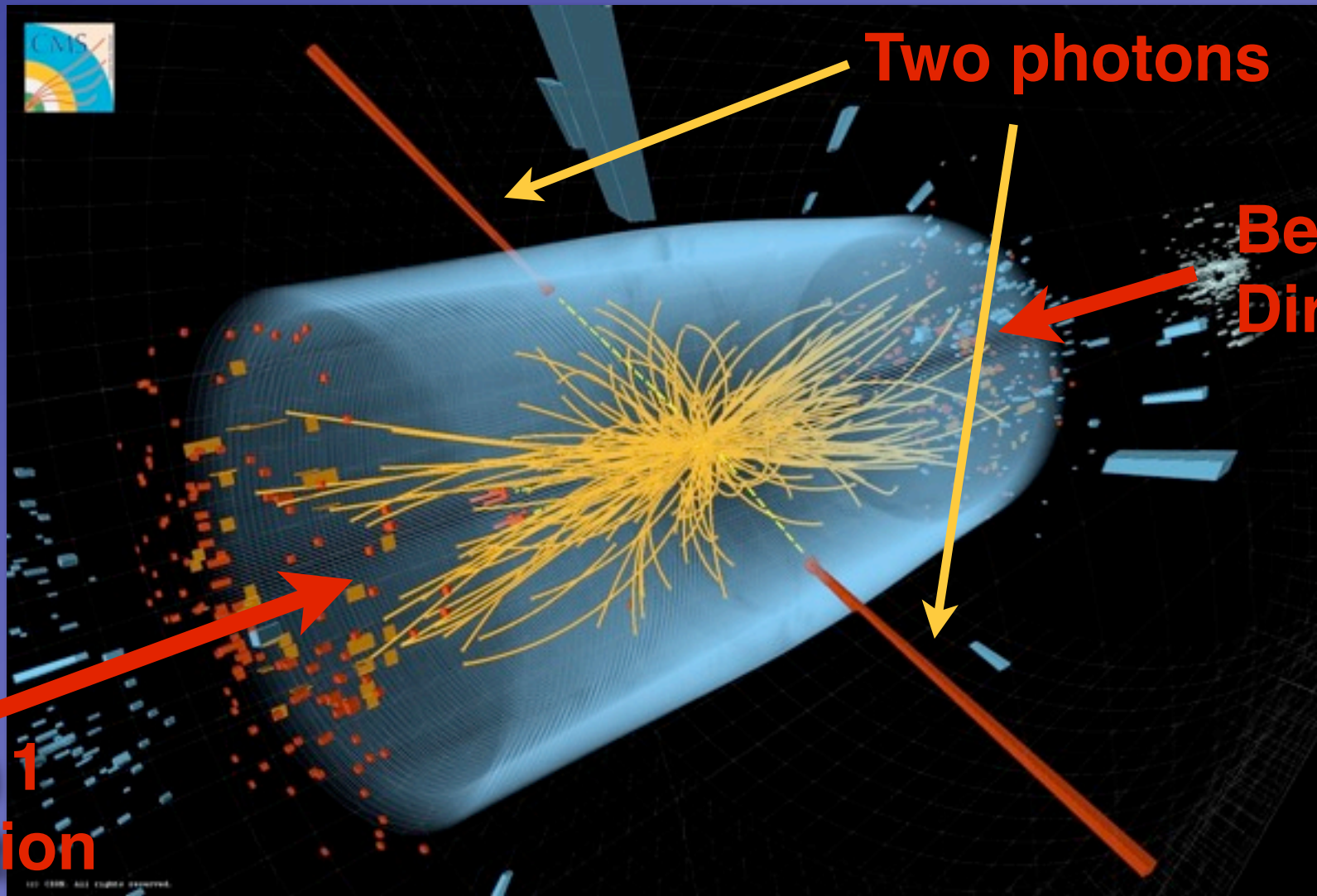
- $H \rightarrow \text{dark matter?!}$

Higgs decays at $m_H=125\text{GeV}$



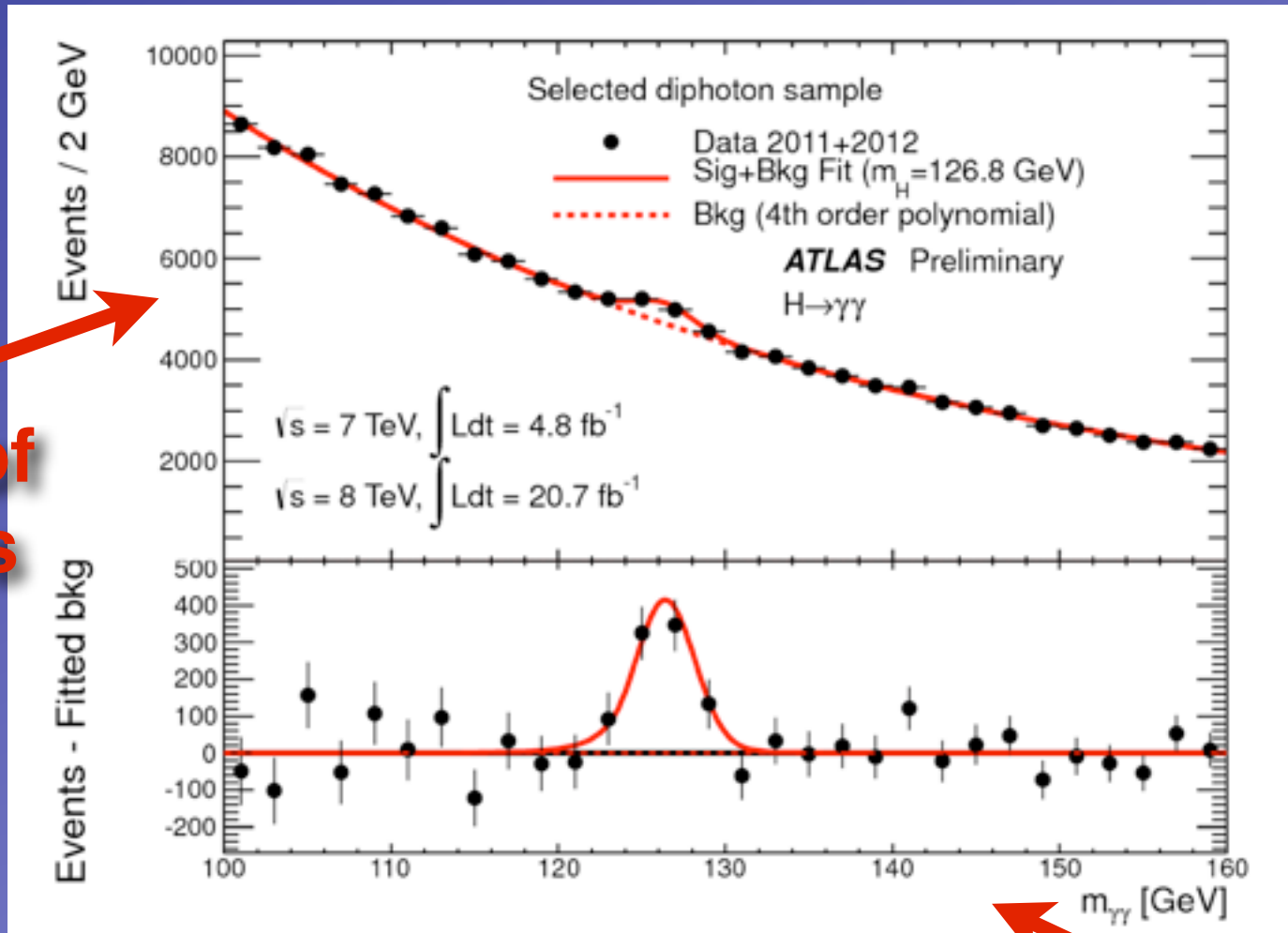
- Each “channel” has different challenges

$H \rightarrow \gamma\gamma$: an example event



γ is a photon which is just very high energy light

$H \rightarrow \gamma\gamma$: the key plot

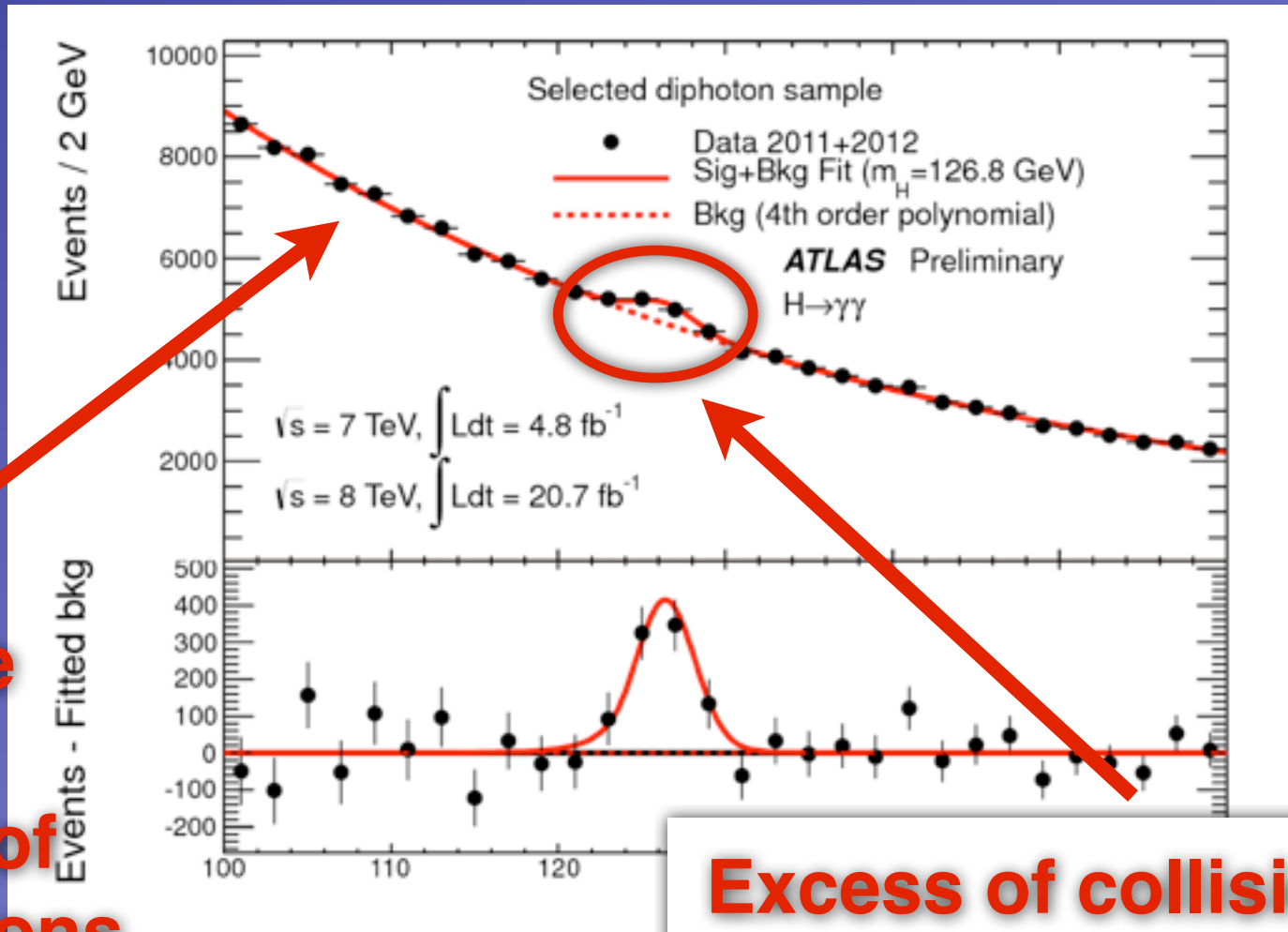


Number of Collisions

$E=mc^2$ so the sum of the energy of the two photons is the Higgs mass

Energy of the two photons

$H \rightarrow \gamma\gamma$: the key plot



There are other sources of two photons

$E=mc^2$ so the sum of the two photons is the

Excess of collisions in one place means they come from a particle with that mass

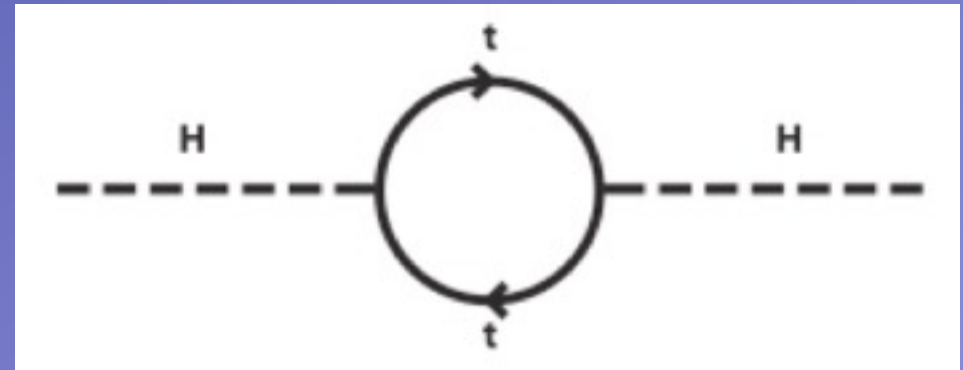
The Future

Many Big Questions Remain

The Higgs itself is an enigma

- Quantum Mechanics tends to make the Higgs very heavy (10^{16} GeV), but it's only 125 GeV

This effect should
change the Higgs mass \longrightarrow
be a very large number



- Could be solved by a new symmetry

*“Supersymmetry” is
one proposed solution*



The Future: Big Questions Remain

Making Dark Matter in the Lab?

Gravity of the stars in the middle of a galaxy pulls stars on edges to keep them in moving in circles



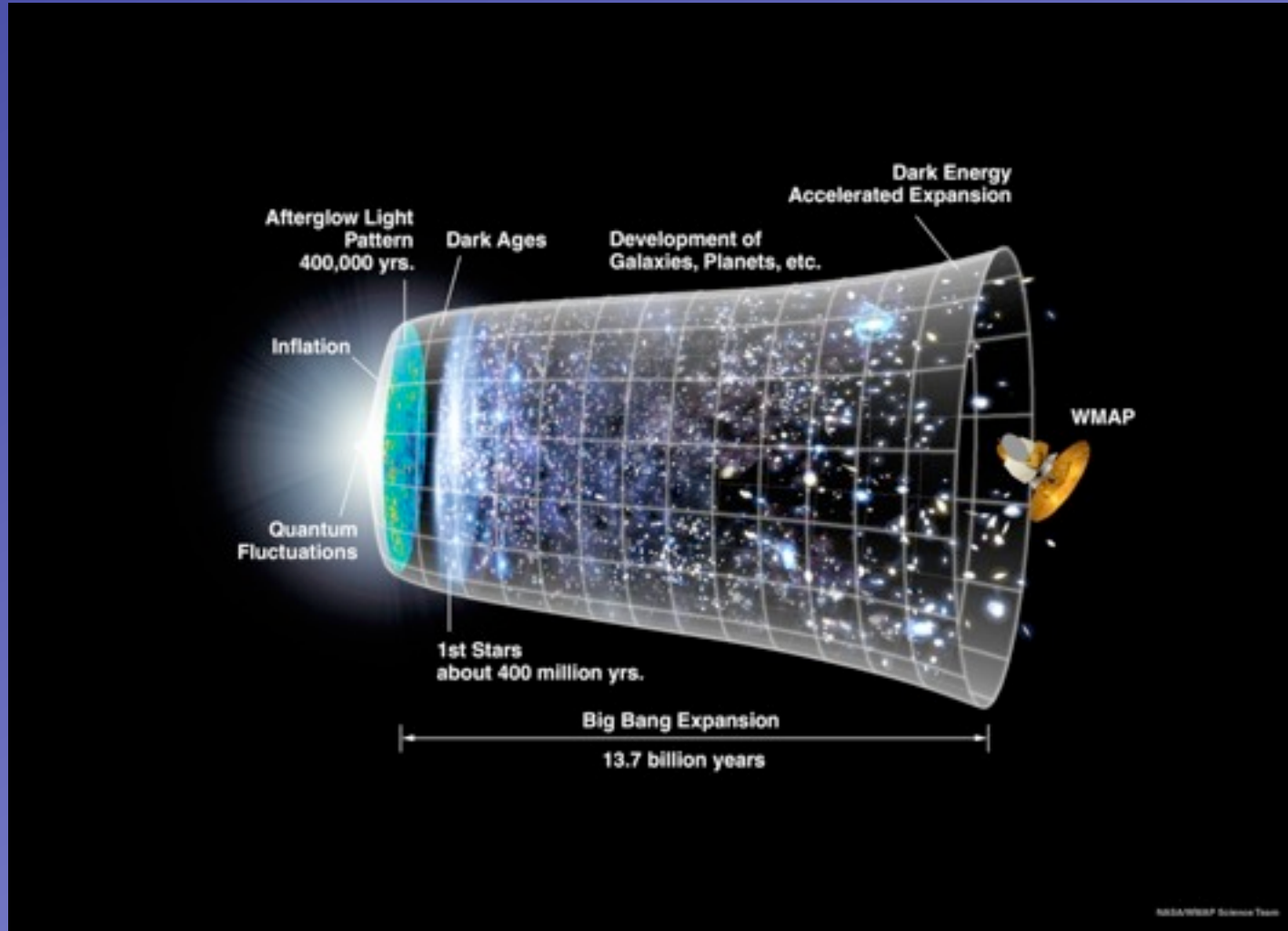
But there aren't enough stars!

We need something in the middle pull in the stars...
Something invisible...
= DARK MATTER



The Future: Big Questions Remain

Making Dark Matter in the Lab?

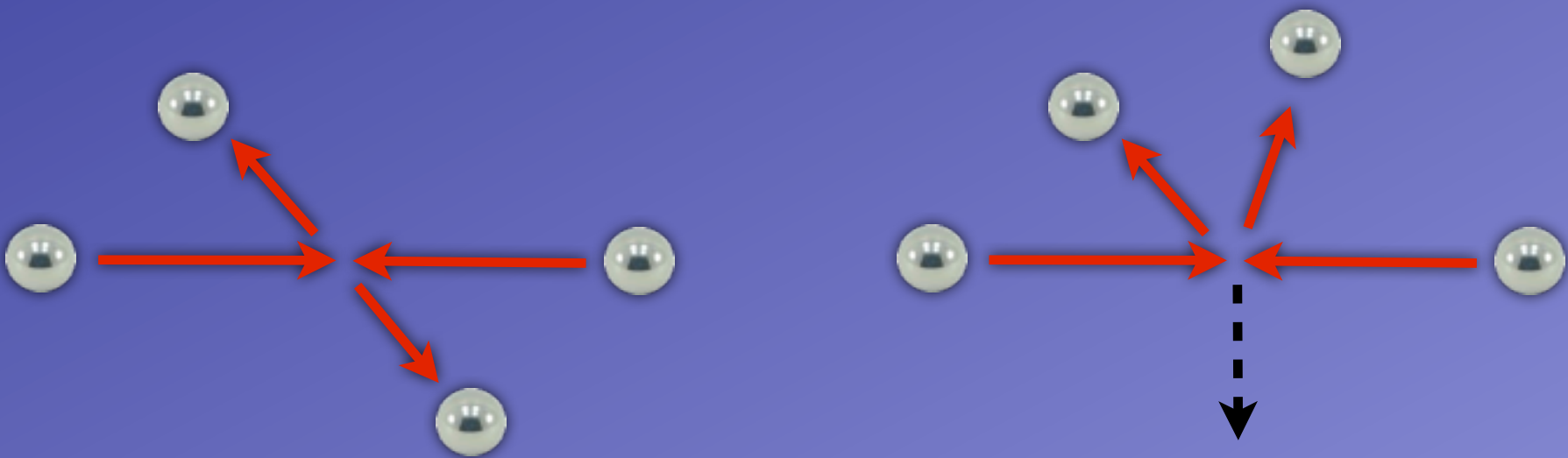


Much more evidence of Dark Matter from the early universe

The Future: Big Questions Remain

Making Dark Matter in the Lab?

How do you detect the invisible?



- Outgoing particles moving in opposite directions
- Momentum balanced
- Nothing missing

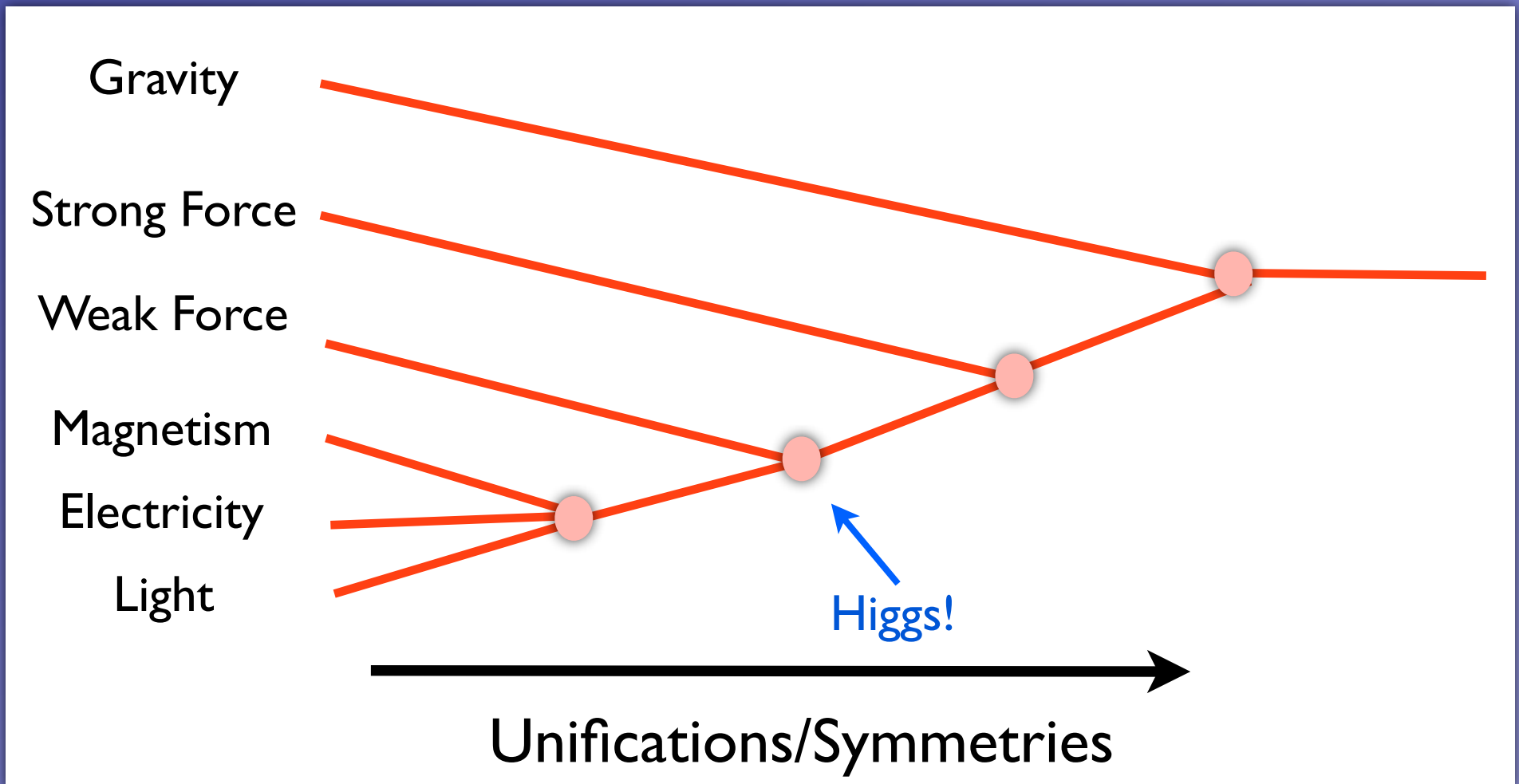
Dark Matter

- Momentum **not** balanced
- Something Missing!
- Discover Dark Matter?!

The Future: Big Questions Remain

Are there simpler models?

- Relating particles to each other by symmetry (“Grand Unified theory”)



Summary

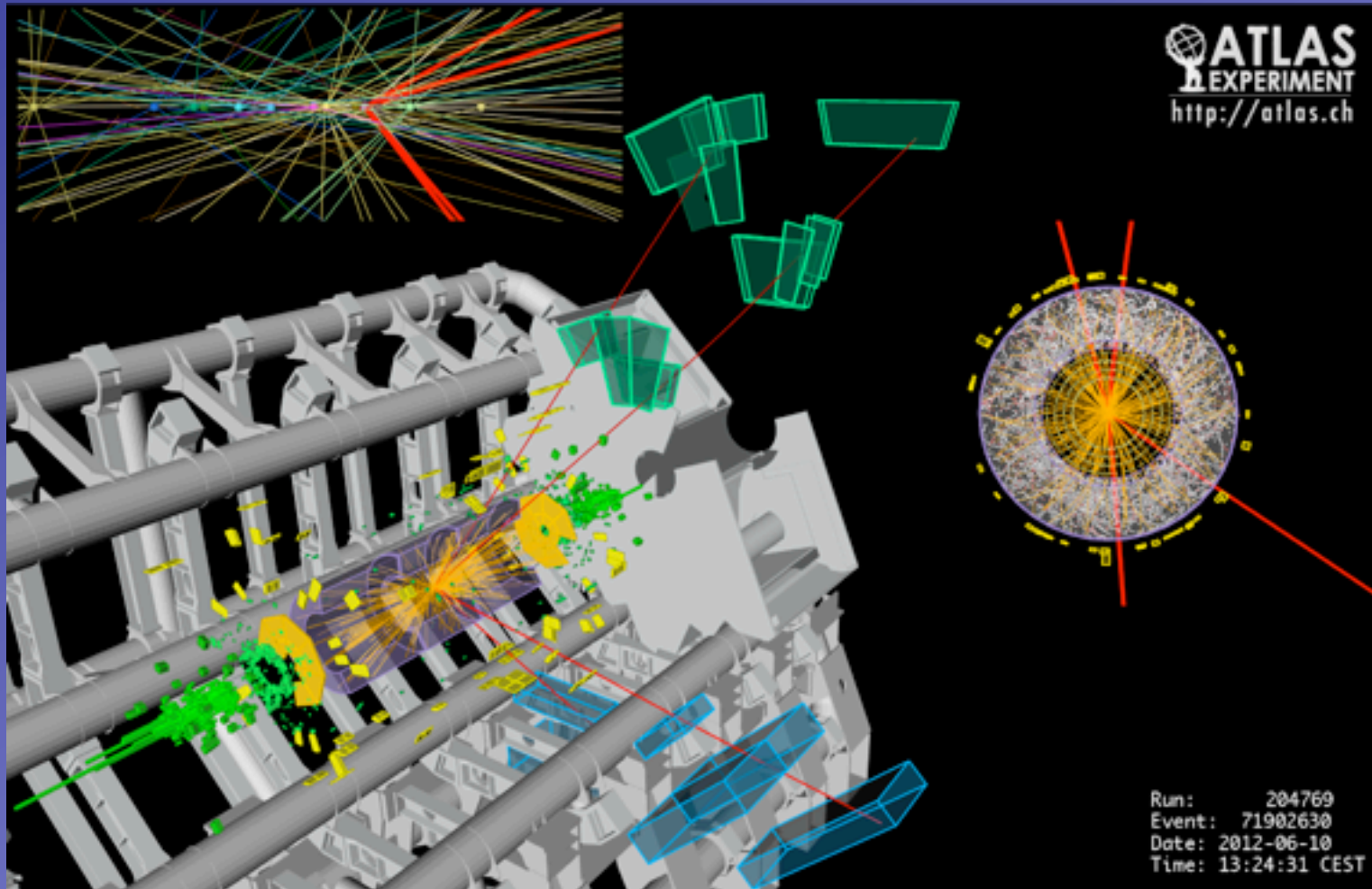


Former directors of CERN at the July 4th, 2012
discovery announcement

We found it! ...and the future is bright

Backup Slides

$$H \rightarrow ZZ$$

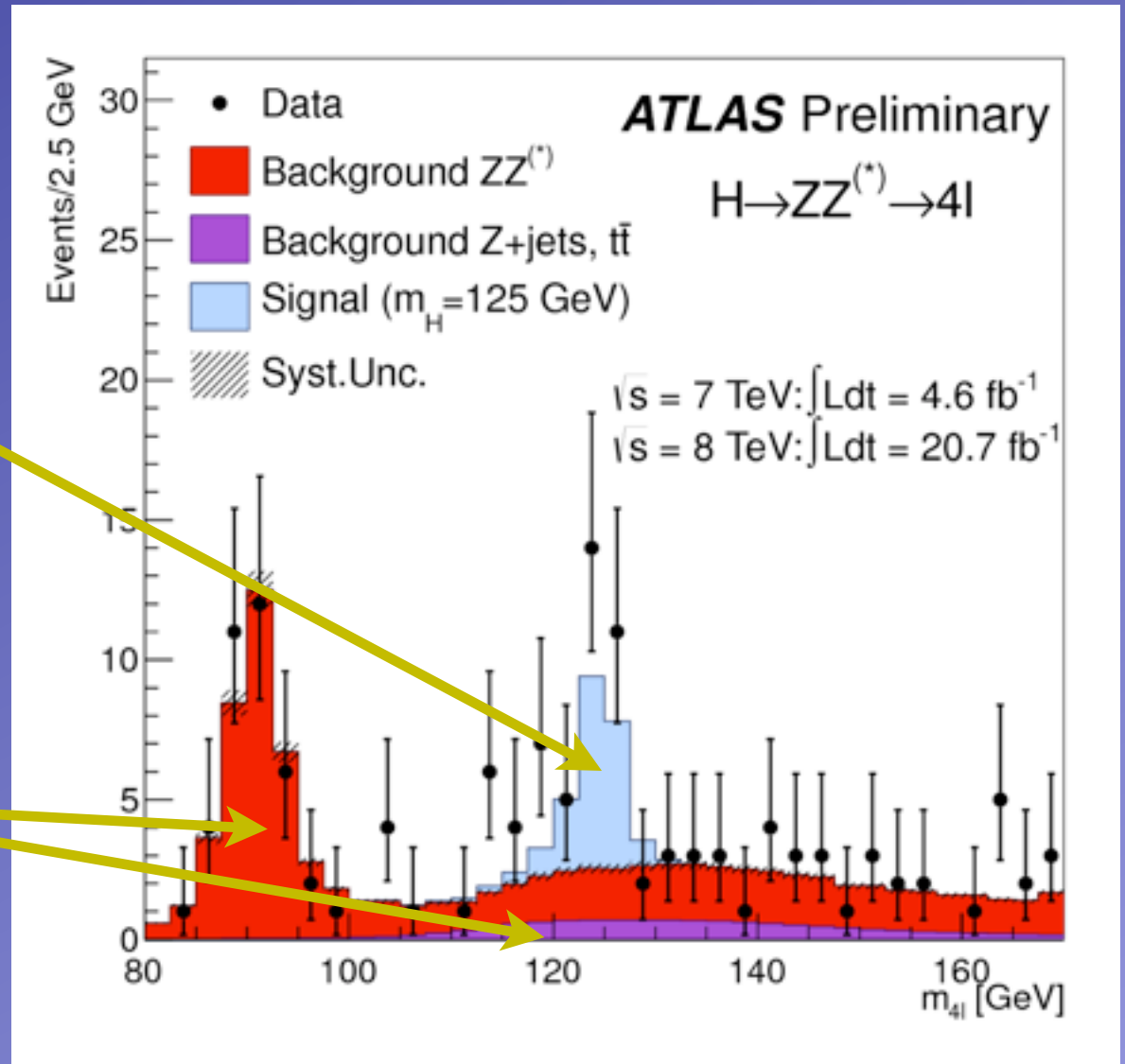


A “Z” is like a heavy photon
Because it’s heavy it decays (recall $E=mc^2$)
This is a $H \rightarrow ZZ \rightarrow \mu\mu \mu\mu$ event

$$H \rightarrow ZZ$$

Excess
indicating
new particle

Predictions
of all known
sources of
events



Plot energy of all four leptons (muons or electrons)
Excess at 125 GeV indicates the presence of the Higgs

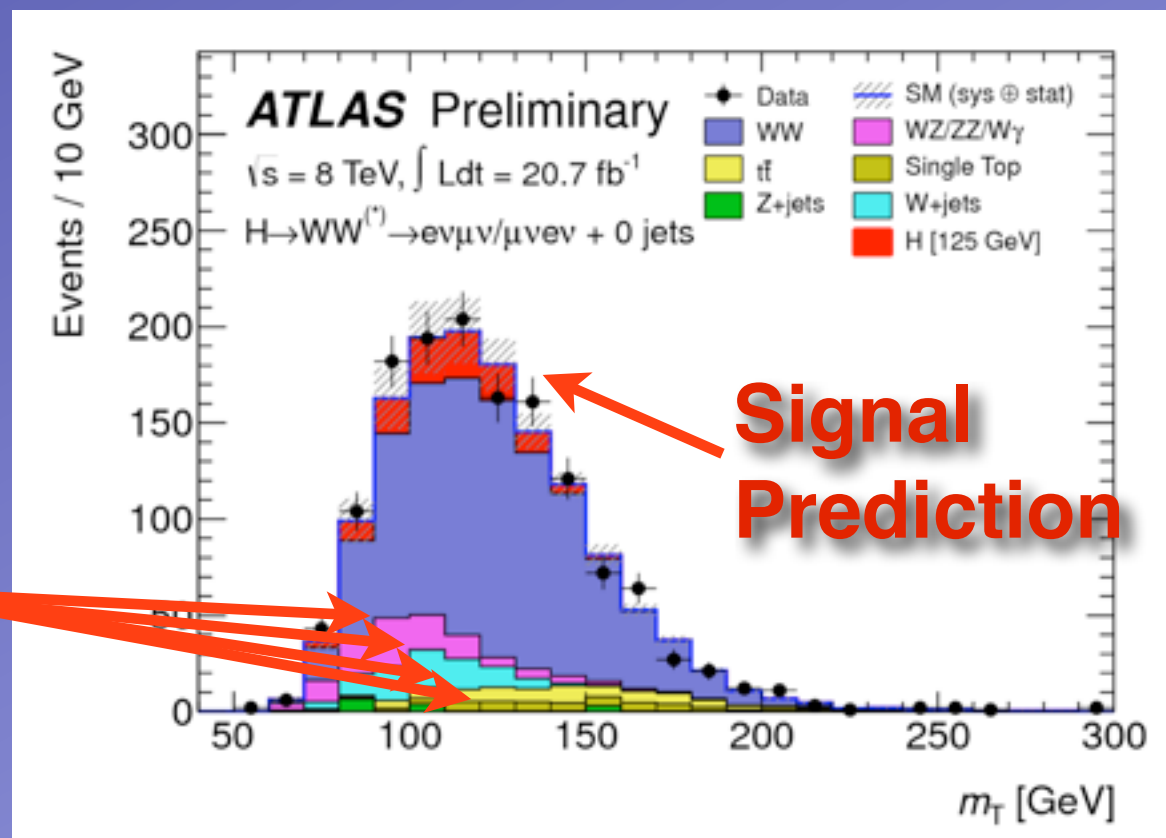
$H \rightarrow WW$

Extra difficult because W decays to an electron or muon and a neutrino...
but our detector can't see neutrinos at all!

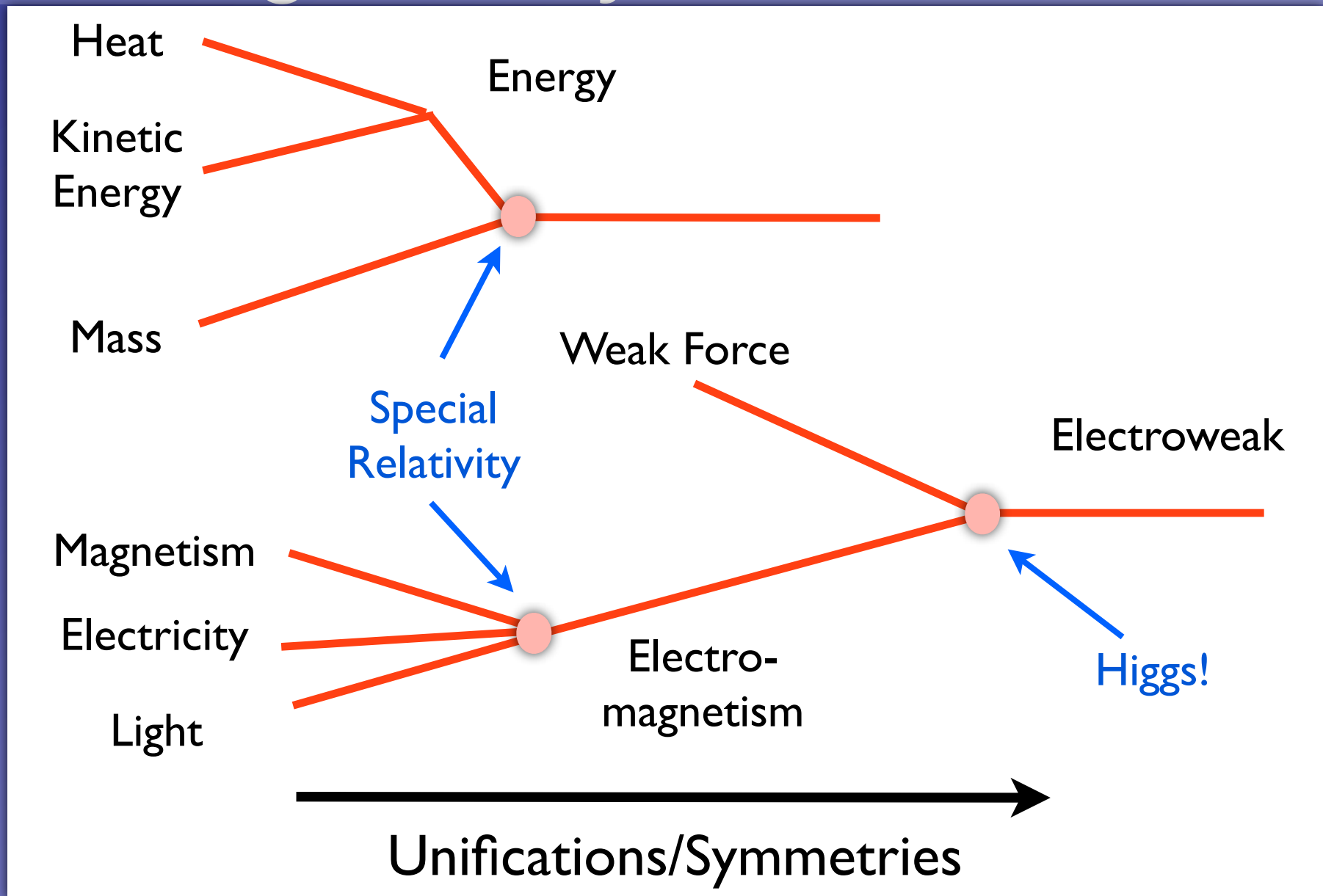
Advantage is that it is much more common

Use momentum conservation to figure out something about what you are missing

Very detailed predictions of all known sources of events

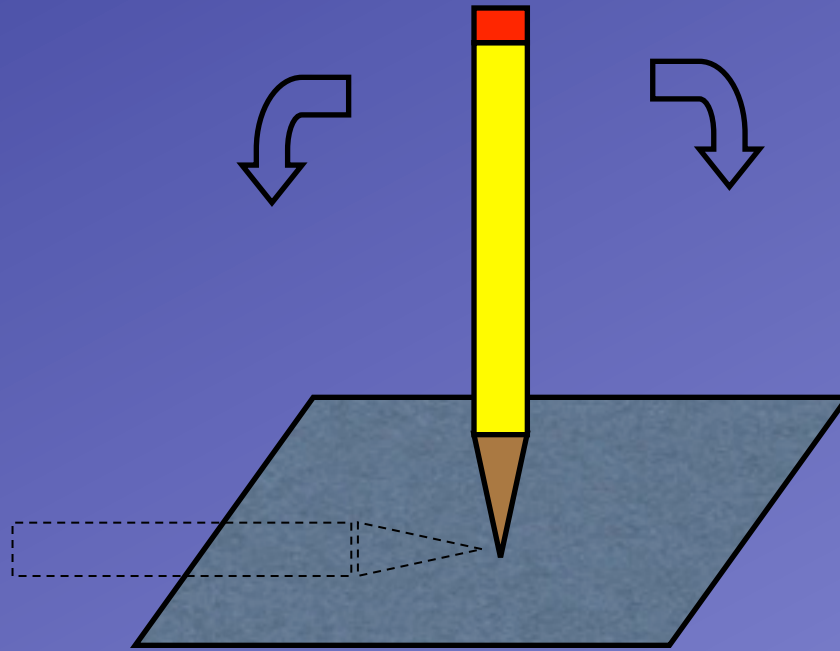


Long History of Unification



Symmetry is really when we realize the two things are manifestations of the same thing

How do you break a symmetry?



The Pencil will pick a direction to fall

The Higgs is setup to pick a direction